DIGITAL COMPUTER SIMULATION FOR SURFACE SHIP CONTROL

Aporn Ratanaruang

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

DIGITAL COMPUTER SIMULATION
FOR
SURFACE SHIP CONTROL

by

Aporn Ratanaruang

Thesis Advisor: M. L. Wilcox

June 1973

Approved for public release; distribution unlimited.

Digital Computer Simulation
for
Surface Ship Control

by

Aporn Ratanaruang
Lieutenant Commander, Royal Thai Navy
Thai Naval Academy, 1957
B.S.E.E., Naval Postgraduage School, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1973

ABSTRACT

The general equations of surface ship motion are developed and standardized for simulation in digital computer. Digital simulations of the dynamics of the surface ship in three degrees of freedom are done with and without non-linear and cross-coupling terms.

TABLE OF CONTENTS

LIST OF TABLES

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Professor MILTON L. WILCOX for the guidance, assistance and continuous encouragement which he provided during the pursuit of this study. The author would also like to express his appreciation to Dr. GEORGE J. THALER for his valuable assistance in furnishing the data for simulation.

I. EQUATIONS OF SURFACE SHIP MOTION

A moving ship is a body with six degrees of freedom. These degrees of freedom are generally chosen as follows:

a. Linear displacements along the three axes through the center of gravity.

a.1 Surge -- along X axes

a.2 Sway -- along Y axes

a.3 Heave -- along Z axes

b. Rotations around the three axes through the center of gravity.

b.1 Roll -- around X axes

b.2 Pitch -- around Y axes

b.3 Yaw -- around Z axes

Further reduction in the complex nature of the equations can be brought about by choosing an orthogonal axis system parallel to the principal axes of inertia so as to eliminate products of inertia in the motion equations. For practically all ocean vehicles, with extremely few exceptions, a longitudinal axis (X axis) in the centerline plane, a downward (toward keel) axis (Z axis) perpendicular to the X axis in the centerline plane, and a transverse axis (Y axis) perpendicular to the centerline plane satisfies this requirement.

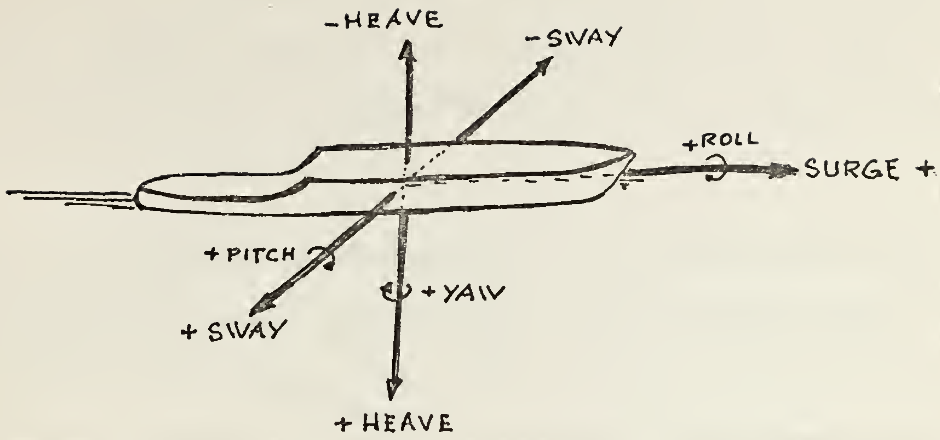

Figure 1. Surface ship in six degrees of freedom.

For the exceptional vehicle which has a very peculiar and significantly large asymmetrical mass distribution, it is necessary to include the products of inertia.

The X, Y, Z axes form an orthogonal right hand system of axes fixed in the vehicle. The axes and the associated components of the pertinent physical quantities are defined below:

The longitudinal X axis (in the plane of symmetry) is positive in the forward direction, usually parallel to the keel or calm water line. If the upper and lower halves of the body are symmetrical, then the axis is the intersection of the two planes of symmetry.

The Y axis is the transverse axis perpendicular to the plane of symmetry and positive to the starboard.

The Z axis or downward axis in the plane of symmetry (X,Z) is perpendicular to the X axis and positive downward towards the keel.

$\hat{i},\hat{j},\hat{k}$ unit vectors along the X,Y,Z axis respectively.

$\vec{R}$ x,y,z vector distance of a point from the origin O, and the corresponding components along the X,Y and Z axes.

$$\vec{R} = ix_G + jy_G + kz_G$$

$\vec{U}$ u,v,w velocity or the origin O (on the body) and the corresponding components along the X,Y and Z axis.

$$\vec{U} = \hat{i}u + \hat{j}v + \hat{k}w$$

$\vec{\Omega}$ p,q,r angular velocity of the body about the origin and the corresponding components about the axes.

$$\vec{\Omega} = \hat{i}p + \hat{j}n + \hat{k}r$$

The moments of inertia of the body about the X,Y and Z axes respectively I_x, I_y, I_z.

$\vec{F}$ X,Y,Z, force acting on the body and the corresponding components along the axes.

$$\vec{F} = \hat{i}X + \hat{j}Y + \hat{k}Z$$

$\vec{m}$ K,M,N Moments acting about the axes.

$$\vec{m} = \hat{i}K + \hat{j}M + \hat{k}N$$

Newton's law of motion for a rigid body can be written as two equations, one a force equation and the second a moment equation provided an origin is taken at the center of gravity and the axis system is fixed in space. The equations are

$$\vec{F} = \frac{d}{dt}\,\overrightarrow{(\text{momentum})} \cdot \frac{d}{dt}\,(m\,\vec{U}_G)$$

$$\vec{m} = \frac{d}{dt}\,\overrightarrow{(\text{angular momentum})}_G = \frac{d}{dt}(I\vec{\Omega})$$

where the subscript G refers to an origin at the center of gravity and m is the mass of the body. For a mass essentially constant in time

$$\vec{F} = m \frac{d}{dt}(\vec{U}_G)$$

For an origin not at the center of gravity of the body and in a system of axes fixed in and moving with the vehicle.

$$\vec{U}_G = U_a + \vec{\Omega} \times \vec{R}_G$$

where U_a is the velocity of the origin in space. However, since the origin is on the surface of the earth and the earth rotates, then

$$\vec{U}_a = \vec{U} + \vec{\Omega}_e \times \vec{R}_b$$

where $\vec{U}$ is the geographical velocity of the body, $\vec{\Omega}_e$ is the angular velocity of the earth, and $\vec{R}_b$ is the radius vector from earth's center to the vehicle. The force equation becomes:

$$\vec{F} = m \frac{d}{dt}(\vec{U} + \vec{\Omega}_e \times \vec{R}_b + \Omega \times \vec{R}_G)$$

$$\vec{F} = m \frac{d}{dt}(\vec{U} + \vec{\Omega} \times \vec{R}_b) + m[\dot{\vec{\Omega}}_e \times \vec{R}_b + \vec{\Omega}_e \times \dot{\vec{R}}_b]$$

$$= m \frac{d}{dt}(\vec{U} + \vec{\Omega} \times \vec{R}_G) + m[\vec{\Omega}_e \times \vec{U} + \vec{\Omega}_e \times \vec{\Omega}_e \times \vec{R}_b]$$

since $\dot{\vec{\Omega}} = 0$ and $\dot{\vec{R}}_b = \vec{U} + \vec{\Omega}_e \times \vec{R}_b$

the term $m\vec{\Omega}_e x\vec{U}$ is the coriolis force and $m\vec{\Omega}_e \times \vec{\Omega}_e \times \vec{R}_b$ is the centripetal acceleration due to rotation of the

earth. These two terms are negligibly small when compared with the other forces, then

$$\vec{F} = m \frac{d}{dt}(\vec{U} + \vec{\Omega} \times R_G)$$

Finding the derivatives of unit vectors (change in direction)

where $d\hat{i} = -\hat{k}d\theta$ $\quad d\hat{i} = \hat{j}d\psi$ $\quad d\hat{i} = 0$

$d\hat{j} = 0$ $\quad d\hat{j} = -\hat{i}d\psi$ $\quad d\hat{j} = \hat{k}d\phi$

$d\hat{k} = \hat{i}d\theta$ $\quad d\hat{k} = 0$ $\quad d\hat{k} = -\hat{j}d\phi$

Adding the contributions

$$\frac{d\hat{i}}{dt} = \hat{i}\cdot 0 + \hat{j}\frac{d\psi}{dt} - \hat{k}\frac{d\theta}{dt}$$

$$\frac{d\hat{j}}{dt} = -\hat{i}\frac{d\psi}{dt} + \hat{j}\cdot 0 + \hat{k}\frac{d\phi}{dt}$$

$$\frac{d\hat{k}}{dt} = \hat{i}\ \frac{d\theta}{dt} - \hat{j}\frac{d\phi}{dt} + \hat{k}\cdot 0$$

$$\vec{\Omega} = \hat{i}p + \hat{j}q + \hat{k}r$$

$$p = \frac{d\phi}{dt}\ ,\ q = \frac{d\theta}{dt}\ ,\ r = \frac{d\psi}{dt}$$

$$\frac{d\hat{i}}{dt} = \vec{\Omega} \times i = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ p & q & r \\ 1 & 0 & 0 \end{vmatrix}$$

$$\vec{U} = \hat{i}u + \hat{j}v + \hat{k}w$$

$$\vec{R}_G = \hat{i}X_G + \hat{j}Y_G + \hat{k}Z_G$$

$$\frac{d\vec{U}}{dt} = \hat{i}\dot{u} + u(\hat{j}\frac{d\hat{i}}{dt} + \hat{j}\dot{v} + v\frac{d\hat{j}}{dt} + \hat{k}\dot{w} + w\frac{d\hat{k}}{dt}$$

$$= \hat{i}\dot{u} + u(\hat{j}\frac{d\psi}{dt} - \hat{k}\frac{d\theta}{dt}) + \hat{j}\dot{v} + v(-\hat{i}\frac{d\psi}{dt} + \hat{k}\frac{d\phi}{dt})$$

$$+ \hat{k}\dot{w} + w(\hat{i}\frac{d\theta}{dt} - \hat{j}\frac{d\phi}{dt})$$

$$= \hat{i}\dot{u} + u(\hat{j}r - \hat{k}q) + \hat{j}\dot{v} + v(-ir + \hat{k}p) + k\dot{w} + w(\hat{i}q - \hat{j}p)$$

$$\vec{\Omega} \times \vec{R}_G = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ p & q & r \\ X_G & Y_G & Z_G \end{vmatrix} = \hat{i}(qZ_G - rY_G) - \hat{j}(pZ_G - rX_G) + \hat{k}(pY_G - qX_G)$$

$$\frac{d}{dt}(\vec{\Omega} \times \vec{R}_G) = \hat{i}(Z_G\dot{q} - Y_G\dot{r}) + \hat{j}(Z_G qr - Y_G r^2) + \hat{k}(Y_G qr - Z_G q^2)$$

$$+ \hat{j}(X_G\dot{r} - Z_G\dot{p}) + \hat{k}(X_G rp - Z_G p^2) + \hat{i}(Z_G rp - X_G r^2)$$

$$+ \hat{k}(Y_G\dot{p} - X_G\dot{q}) + \hat{i}(Y_G pq - X_G q^2) + \hat{j}(X_G pq - Y_G p^2)$$

from $\vec{F} = \hat{i}X + \hat{j}Y + \hat{k}Z$ and $\vec{F} = m[\frac{d\vec{U}}{dt} + \frac{d}{dt}(\vec{\Omega} \times \vec{R}_G)$

Rewriting and grouping all $\hat{i}$ terms equal to X, all $\hat{j}$ terms equal to Y and all $\hat{k}$ terms equal to Z yield

$$X = m(\dot{u} - vr + wg + Z_G\dot{q} + rpZ_G - r^2X_G + pqY_G - q^2X_G)$$

$$= m(\dot{u} + wg - vr - X_G(r^2 + q^2) + Y_G(pq - \dot{r}) + Z_G(rp + \dot{q})$$

$$Y = m(\dot{v} + ur - wp + X_G(pq + \dot{r}) - Y_G(p^2 + r^2) + Z_G(pq - \dot{r}) \qquad (1)$$

$$Z = m(\dot{w} + vp - uq + X_G(rp - \dot{q}) + Y_G(qr + \dot{p}) - Z_G(p^2 + q^2)$$

From $\vec{m}_G = \frac{d}{dt}(\text{angular momentum})_G$

$$= \frac{d}{dt}(\hat{i}I_{X_G}p + \hat{j}I_{Y_G}q + \hat{k}I_{Z_G}r)$$

G indicates an origin at the center of gravity

$$I_{X_G} = I_X - m(Y_G^2 + Z_G^2)$$

$$I_{Y_G} = I_Y - m(Z_G^2 + X_G^2)$$

$$I_{Z_G} = I_Z - m(X_G^2 + Y_G^2)$$

$$\vec{M} = \vec{M}_G + \vec{R}_G \times \vec{F} \quad \text{or} \quad \vec{M}_G = \vec{M} - \vec{R}_G \times \vec{F}$$

After manipulating and using the results for the derivatives of unit vectors (same as above) expressions for K, H and N are obtained.

$$K = I_X\dot{p} + (I_Z - I_Y)qr + m[Y_G(\dot{w} + pv - qu) - Z_G(\dot{v} + ru - pw)]$$

$$M = I_Y\dot{q} + (I_X - I_Z)rp + m[Z_G(\dot{u} + qw - rv) - X_G(\dot{w} + pv - qu)] \qquad (2)$$

$$N = I_Z\dot{r} + (I_Y - I_X)pq + m[X_G(\dot{v} + ru - pw) - Y_G(\dot{u} + qw - rv)]$$

The terms (qw-rv), (ru-pw) and (pv-qu) are gyroscopic effects.

The relationship for forces and moments can be expressed

$$\left.\begin{array}{r}\text{Force}\\ \\ \text{Moment}\end{array}\right) = f(\text{properties of body, properties of motion, properties of fluid})$$

For a particular ship, in a given fluid with no excitation force - so

$$\left.\begin{array}{r}\vec{F}\\ \\ \vec{M}\end{array}\right) = f(\text{properties of motion})$$

$$= f(X_o, Y_o, Z_o, \phi, \theta, \psi, u, v, w, p, q, r, \dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}, \delta, \delta', \delta'')$$

The Taylor series which has the following form may now be applied to linearize the equations about an operating point $\overline{X}_o$

$$f(X) = f(\overline{X}_o) + (X-\overline{X}_o)\frac{d}{dx} f(\overline{X}_o) + (X-\overline{X}_o)^2 \frac{d^2}{dX^2} f(\overline{X}_o) + \ldots.$$

Apply this to $f(X,Y,Z)$........

For the case of f(properties of motion) let $(X-\overline{X}_o) = \Delta X_o$, $(Y-\overline{Y}_o) = \Delta Y_o$ and $(Z-Z_o) = \Delta Z_o$ terms second order and higher are neglected for small perturbations.

From X equation the linear terms are obtained:

$$X = f(---)_o + \Delta X_o(\frac{\delta f}{\partial X_o}) + \Delta Y_o(\frac{\delta f}{\partial Y_o}) + \Delta Z_o(\frac{\delta f}{\partial Z_o}) + \ldots \Delta v(\frac{\delta f}{\partial v}) + \ldots$$

The defining relations are:

$$(\frac{\delta f}{\delta u})_o = (\frac{\delta X}{\delta u})_{u=u_o} = X_u$$

$$(\frac{\delta X}{\delta w})_{w=w_o} = X_w$$

$$\Delta w = (w-w_o) = w, \quad w_o = 0$$

$$\Delta u = (u-u_o)$$

The force equations then become

$$\begin{aligned} X &= X_o + X_{X_o} X_o + X_{Y_o} Y_o + \ldots X_\theta \theta + \ldots X_u \Delta_u \\ Y &= Y_o + Y_{X_o} X_o + Y_{Y_o} Y_o + \ldots Y_\theta \theta + \ldots Y_u \Delta_u \\ Z &= Z_o + Z_{X_o} X_o + Z_{Y_o} Y_o + \ldots Z_\theta \theta + \ldots Z_u \Delta_u \end{aligned} \tag{3}$$

A similar derivation can be done for the K,M and N equations. The preceding X,Y and Z equations may now be equated to the linearized X,Y and Z (equations (1)), e.g., for the Y equation without roll, pitch, and the center of gravity at $X_G = 0$, $Y_G = 0$ and $Z_G = 0$ gives the linearized equation.

$$Y = m(\dot{v} + ur)$$

then

$$Y_{X_o} X_o + Y_{Y_o} Y_o + Y_\psi \psi + Y_u u + Y_v v + Y_r r + Y_{\dot{u}} \dot{u} + Y_{\dot{v}} \dot{v} + Y_{\dot{r}} \dot{r} = m(\dot{v}+ru)$$

Expressions for X,Z and K,M and N can be determined in a similar procedure.

In order to obtain the equations in a non-dimensional form some definitions will be given, and applied to the Y force equations as an example of the process.

$$\text{Froude number} = \frac{U}{\sqrt{g\ell}}$$

$$u'.v',w' = \frac{u,v,w}{\sqrt{g/\ell}}$$

$$t' = t(\sqrt{g/\ell})$$

$$X',Y',Z' = \frac{X,Y,Z}{\rho g \ell^3}$$

$$C_X',C_Y',C_Z' = \frac{X,Y,Z}{\frac{1}{2}\rho U^2 \ell^2}$$

After replacing and adding the effect of waves, the Y equation becomes:

$$\dot{v}' + r'u' = \frac{1}{2} U^{2\prime} (C_{Y_{v'}} v' + C_{Y_{p'}} p' + C_{Y_{r'}} r' + C_{Y_{\delta r}} \delta r)$$
$$+ (Y_{\dot{p}'} \dot{p}' + Y_{\dot{v}} \dot{v}' + Y_{\dot{r}'} \dot{r}' + Y_w')$$

II. DIGITAL COMPUTER SIMULATION

The six equations of motion after rearranging by placing the second order terms to the left and the rest on the right side become:

$$
\begin{aligned}
aa\ddot{A}+ba\ddot{B}+ca\ddot{C}+da\ddot{D}+ea\ddot{E}+fa\ddot{F} = & -(a_1a_1\dot{A}+a_2a_2A+b_1a_1\dot{B}+b_2a_2B \\
& + c_1a_1\dot{C}+c_2a_2C+d_1a_1\dot{D}+d_2a_2D \\
& + e_1a_1\dot{E}+e_2a_2E+f_1a_1F+f_2a_2F) \\
& + IF1
\end{aligned}
$$

$$
\begin{aligned}
ab\ddot{A}+bb\ddot{B}+cb\ddot{C}+db\ddot{D}+eb\ddot{E}+fb\ddot{F} = & -(a_1b_1\dot{A}+a_2b_2A+b_1b_1\dot{B}+b_2b_2B \\
& + c_1b_1\dot{C}+c_2b_2C+d_1b_1\dot{D}+d_2b_2D \\
& + e_1b_1\dot{E}+e_2b_2E+f_1b_1F+f_2b_2F) \\
& + IF2
\end{aligned}
$$

$$
\begin{aligned}
ac\ddot{A}+bc\ddot{B}+cc\ddot{C}+dc\ddot{D}+ec\ddot{E}+fc\ddot{F} = & -(a_1c_1\dot{A}+a_2c_2A+b_1c_1\dot{B}+b_2c_2B \\
& + c_1c_1\dot{C}+c_2c_2C+d_1c_1\dot{D}+d_2c_2D \\
& + e_1c_1\dot{E}+e_2c_2E+f_1c_1\dot{F}+f_2c_2F) \\
& + IF3
\end{aligned}
$$

$$
\begin{aligned}
ad\ddot{A}+bd\ddot{B}+cd\ddot{C}+dd\ddot{D}+ed\ddot{E}+fd\ddot{F} = & -(a_1d_1\dot{A}+a_2d_2A+b_1d_1\dot{B}+b_2d_2B \\
& + c_1d_1\dot{C}+c_2d_2C+d_1d_1D+d_2d_2D \\
& + e_1d_1\dot{E}+e_2d_2E+f_1d_1\dot{F}+f_2d_2F) \\
& + IF4
\end{aligned}
$$

$$
\begin{aligned}
ae\ddot{A}+be\ddot{B}+ce\ddot{C}+de\ddot{D}+ee\ddot{E}+fe\ddot{F} = & -(a_1e_1\dot{A}+a_2e_2A+b_1e_1\dot{B}+b_2e_2B \\
& + c_1e_1\dot{C}+c_2e_2C+d_1e_1D+d_2e_2D \\
& + e_1e_1\dot{E}+e_2e_2E+f_1e_1F+f_2e_2F) \\
& + IF5
\end{aligned}
$$

$$a f\ddot{A}+b f\ddot{B}+c f\ddot{C}+d f\ddot{D}+e f\ddot{E}+f f\ddot{F} = -(a_1 f_1\dot{A}+a_2 f_2 A+b_1 f_1\dot{B}+b_2 f_2 B$$

$$+ c_1 f_1\dot{C}+c_2 f_2 C+d_1 f_1\dot{D}+d_2 f_2 D$$

$$+ e_1 f_1\dot{E}+e_2 f_2 E+f_1 f_1\dot{F}+f_2 f_2 F)$$

$$+ IF6$$

where $\ddot{A}=\dot{u}$, $\dot{A}=u$, $\ddot{B}=\dot{v}$, $\dot{B}=v$, $\ddot{C}=\dot{w}$, $\dot{C}=w$, $\ddot{D}=\dot{p}$, $\dot{D}=p$

$\ddot{E}=\dot{q}$, $\dot{E}=q$, $\ddot{F}=\dot{r}$, $\dot{F}=r$, terms IF include all non-linear terms such as wave force, wind, rudder deflection---etc.

In the six equations, the right can be set equal to I_1, I_2,------I_6 respectively, thus:

$$I_1 = -(a_1 a_1\dot{A}+a_2 a_2 A+b_1 a_1 B+ \text{----------} f_2 a_2 F) + IF1$$

$$I_2 = -(a_1 b_1\dot{A}+a_2 b_2 A+b_1 b_1 B+ \text{----------} f_2 b_2 F) + IF2$$

$$I_3 = -(a_1 c_1\dot{A}+a_2 c_2 A+b_1 c_1 B+ \text{----------} f_2 c_2 F) + IF3$$

$$I_4 = -(a_1 d_1\dot{A}+a_2 d_2 A+b_1 d_1 B+ \text{----------} f_2 d_2 F) + IF4$$

$$I_5 = -(a_1 e_1\dot{A}+a_2 e_2 A+b_1 e_1 B+ \text{----------} f_2 e_2 F) + IF5$$

$$I_6 = -(a_1 f_1\dot{A}+a_2 f_2 A+b_1 f_1 B+ \text{----------} f_2 f_2 F) + IF6$$

the equations then have the form that follows,

$$aa\ddot{A} + ba\ddot{B} + ca\ddot{C} + da\ddot{D} + ea\ddot{E} + fa\ddot{F} = I_1$$

$$ab\ddot{A} + bb\ddot{B} + cb\ddot{C} + db\ddot{D} + eb\ddot{E} + fb\ddot{F} = I_2$$

$$ac\ddot{A} + bc\ddot{B} + cc\ddot{C} + dc\ddot{D} + ec\ddot{E} + fc\ddot{F} = I_3$$

$$ad\ddot{A} + bd\ddot{B} + cd\ddot{C} + dd\ddot{D} + ed\ddot{E} + fd\ddot{F} = I_4$$

$$ae\ddot{A} + be\ddot{B} + ce\ddot{C} + de\ddot{D} + ee\ddot{E} + fe\ddot{F} = I_5$$

$$af\ddot{A} + bf\ddot{B} + cf\ddot{C} + df\ddot{D} + ef\ddot{E} + ff\ddot{F} = I_6$$

expressing in matrix form:

$$\begin{vmatrix} aa & ba & ca & da & ea & fa \\ ab & bb & cb & db & eb & fb \\ ac & bc & cc & dc & ec & fc \\ ad & bd & cd & dd & ed & fd \\ ae & be & ce & de & ee & fe \\ af & bf & cf & df & ef & ff \end{vmatrix} \begin{vmatrix} \ddot{A} \\ \ddot{B} \\ \ddot{C} \\ \ddot{D} \\ \ddot{E} \\ \ddot{F} \end{vmatrix} = \begin{vmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{vmatrix}$$

Apply Cramer's rule to solve for $\ddot{A}$, $\ddot{B}$ ---------- $\ddot{F}$ in terms of I_1 -- I_6

$$\ddot{A} = \frac{\begin{vmatrix} I_1 & ba & ca & da & ea & fa \\ I_2 & bb & cb & db & eb & fb \\ I_3 & bc & cc & dc & ec & fc \\ I_4 & bd & cd & dd & ed & fd \\ I_5 & be & ce & de & ee & fe \\ I_6 & bf & cf & df & ef & ff \end{vmatrix}}{\begin{vmatrix} aa & ba & ca & da & ea & fa \\ ab & bb & cb & db & eb & fb \\ ac & bc & cc & dc & ec & fc \\ ad & bd & cd & dd & ed & fd \\ ae & be & ce & de & ee & fe \\ af & bf & cf & df & ef & ff \end{vmatrix}}$$

define the denominator determinant $\stackrel{\Delta}{=} \Delta$ and for the nominator let cofactor of $I_1 \stackrel{\Delta}{=}$ cof. aa cofactor of $I_2 \stackrel{\Delta}{=}$ cof. ab, ---------and coefactor of I_6 $\stackrel{\Delta}{=}$ cof. af equations becomes:

$$\ddot{A} = \frac{(\text{cof.aa}I_1+\text{cof.ab}I_2+\text{cof.ac}I_3+\text{cof.ad}I_4+\text{cof.ae}I_5+\text{cof.af}I_6)}{\Delta}$$

In the same way solve for B, C, ----------

$$\ddot{B} = \frac{(\text{cof } baI_1 \text{ cof } bbI_2 \text{ cof } bcI_3 \text{ cof } bdI_4 \text{ cof } beI_5 \text{ cof } bfI_6)}{\Delta}$$

$$\ddot{C} = \frac{(\text{cof } caI_1 \text{ cof } cbI_2 \text{ cof } ccI_3 \text{ cof } cdI_4 \text{ cof } ceI_5 \text{ cof } cfI_6)}{\Delta}$$

$$\ddot{D} = \frac{(\text{cof } daI_1 \text{ cof } dbI_2 \text{ cof } dcI_3 \text{ cof } ddI_4 \text{ cof } deI_5 \text{ cof } dfI_6)}{\Delta}$$

$$\ddot{E} = \frac{(\text{cof } eaI_1 \text{ cof } ebI_2 \text{ cof } ecI_3 \text{ cof } edI_4 \text{ cof } eeI_5 \text{ cof } efI_6)}{\Delta}$$

$$\ddot{F} = \frac{(\text{cof } faI_1 \text{ cof } fbI_2 \text{ cof } fcI_3 \text{ cof } fdI_4 \text{ cof } feI_5 \text{ cof } ffI_6)}{\Delta}$$

Then the value of $\dot{A}$, A, $\dot{B}$, B --------- $\dot{F}$, F by integration such that

$$\dot{A} = \frac{dA}{dt} = \int \frac{d^2A}{dt^2} \, , \quad A = \int \frac{dA}{dt}$$

A block diagram to compute all of the variables in the set of equations is presented in Fig. 2.

In the computer program that is used for simulation all six equations for six degrees of freedom are used, but are interested in less than six degrees of freedom. The same program can be used by setting the coupling terms of non-used equations equal to zero and one in terms of principal diagonal, e.g. only three degrees of freedom are used in this study, surge, sway and yaw, then all coupling terms

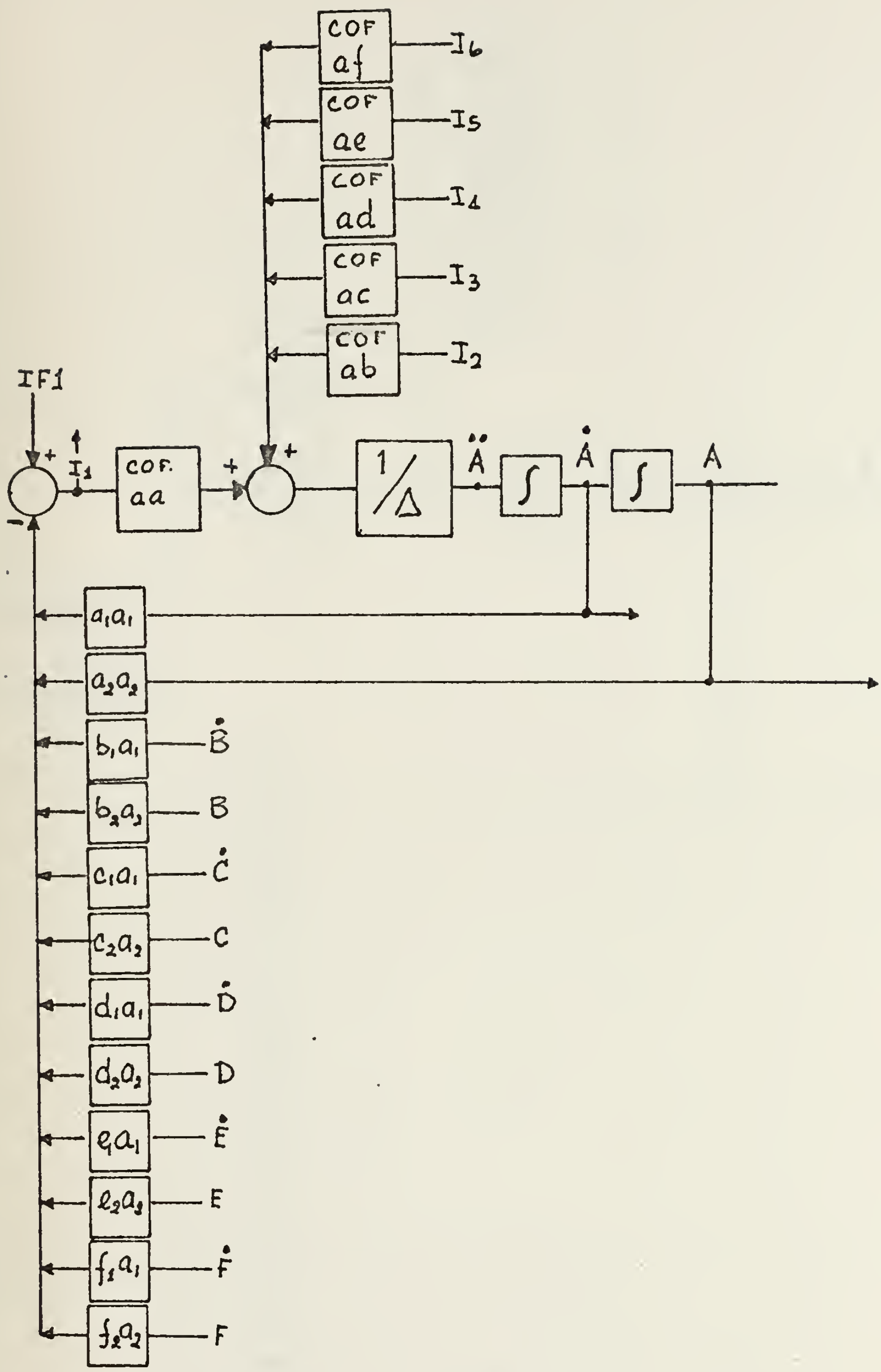

Fig. 2

TRANSFER FUNCTION BLOCK DIAGRAM SIX DEGREES OF FREEDOM(Eqn.A)

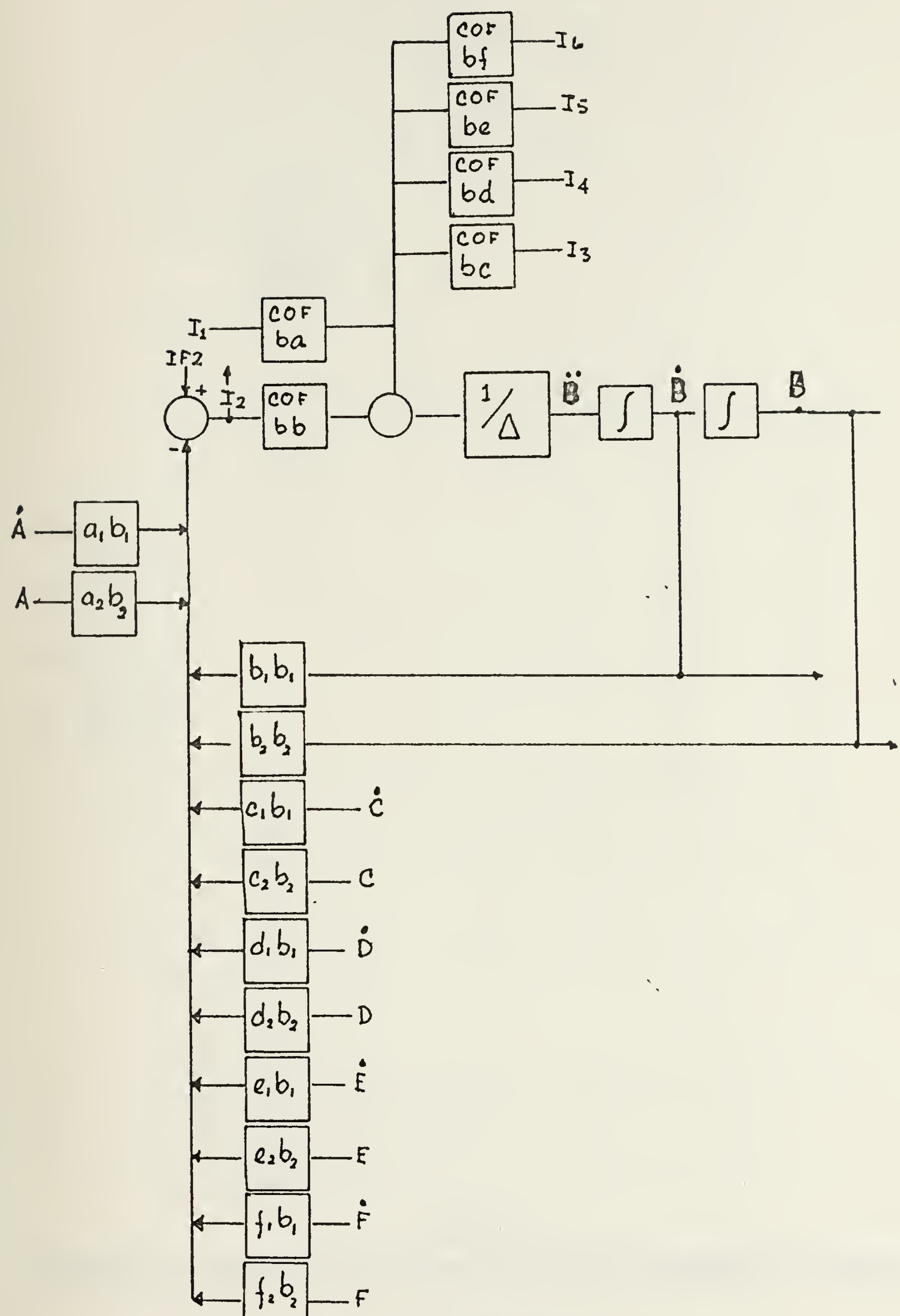

Fig. 2

TRANSFER FUNCTION BLOCK DIAGRAM SIX DEGREES OF FREEDOM(Eqn.B)

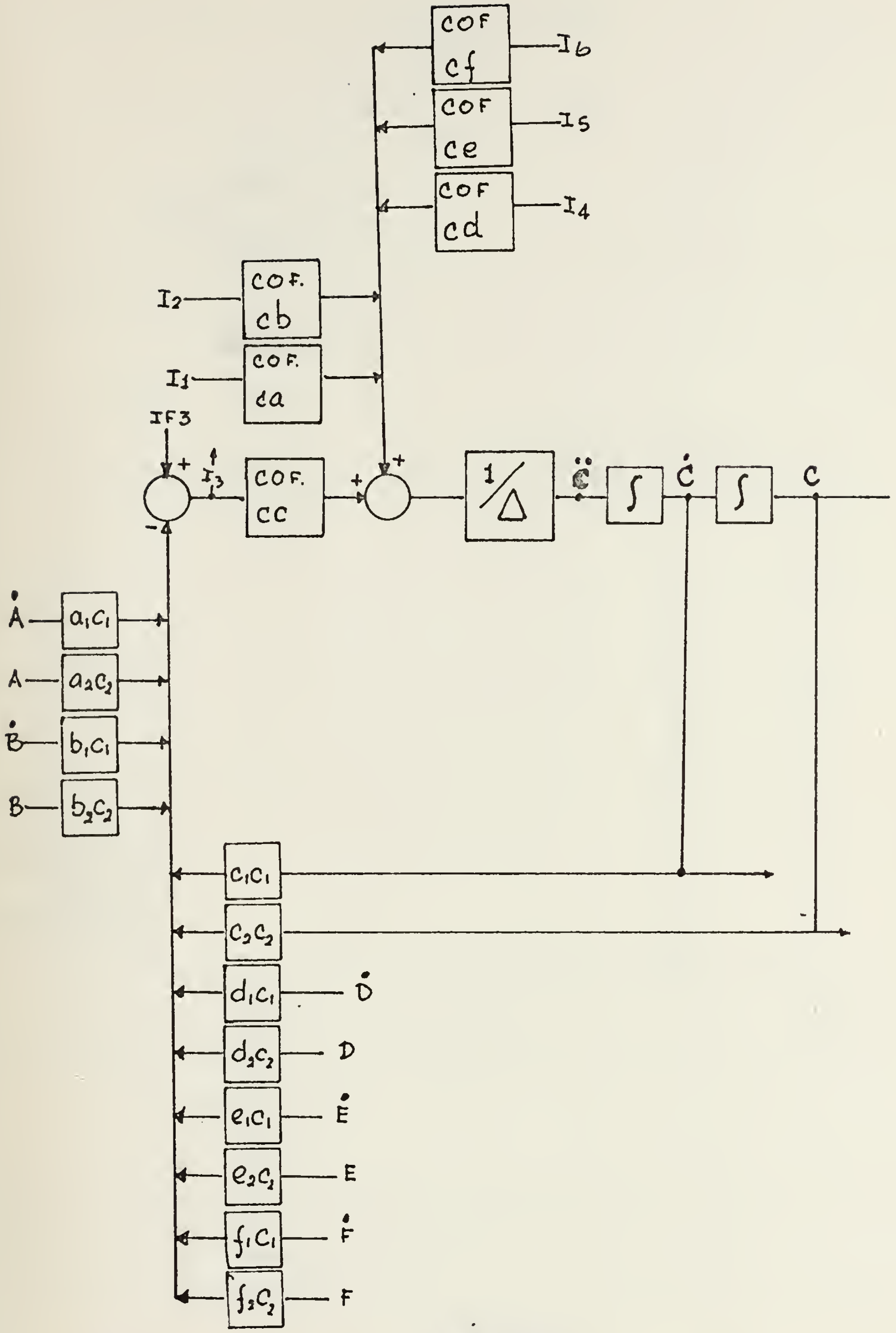

Fig. 2

TRANSFER FUNCTION BLOCK DIAGRAM SIX DEGREES OF FREEDOM(Eqn.C)

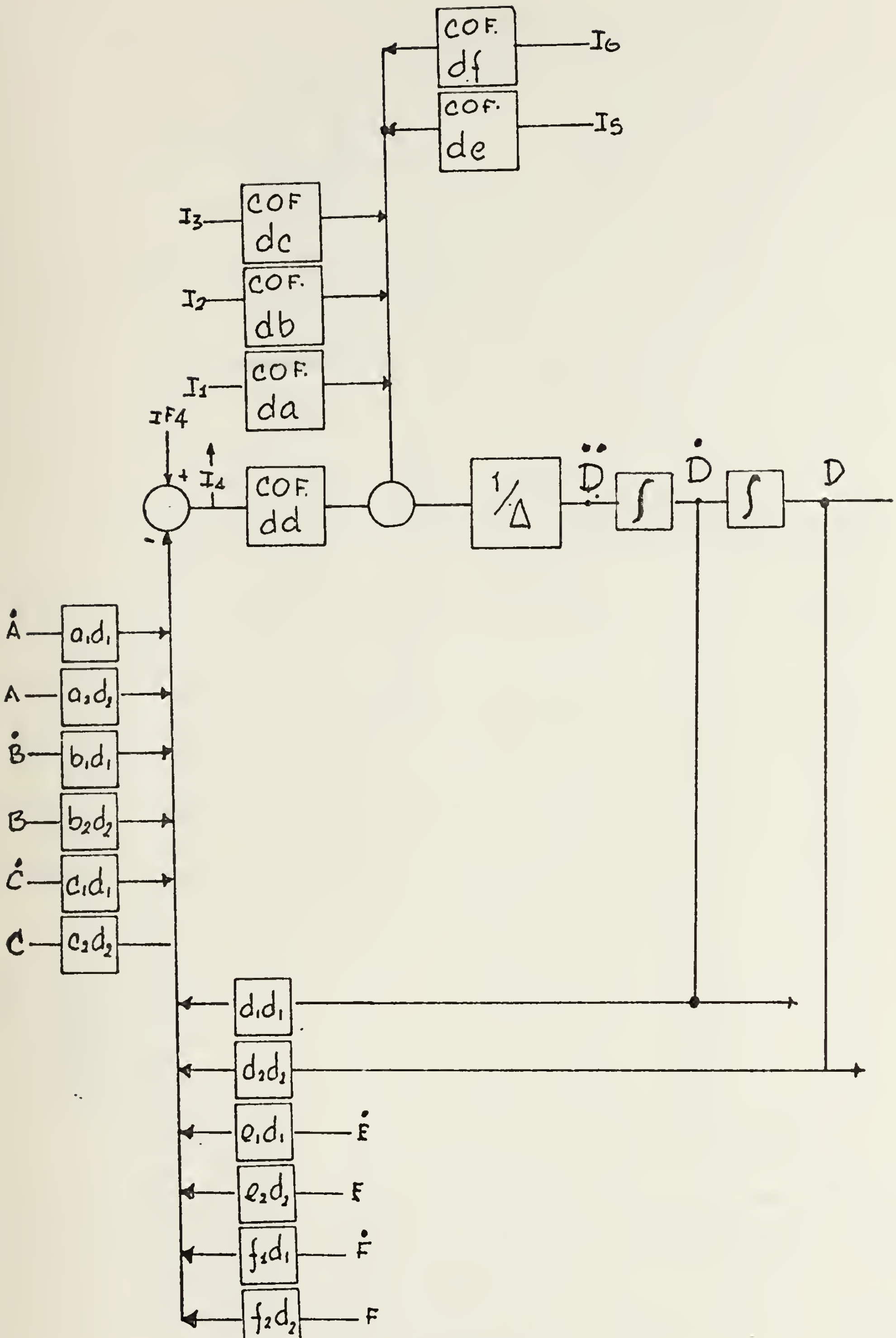

Fig. 2

TRANSFER FUNCTION BLOCK DIAGRAM SIX DEGREE OF FREEDOM(Eqn.D)

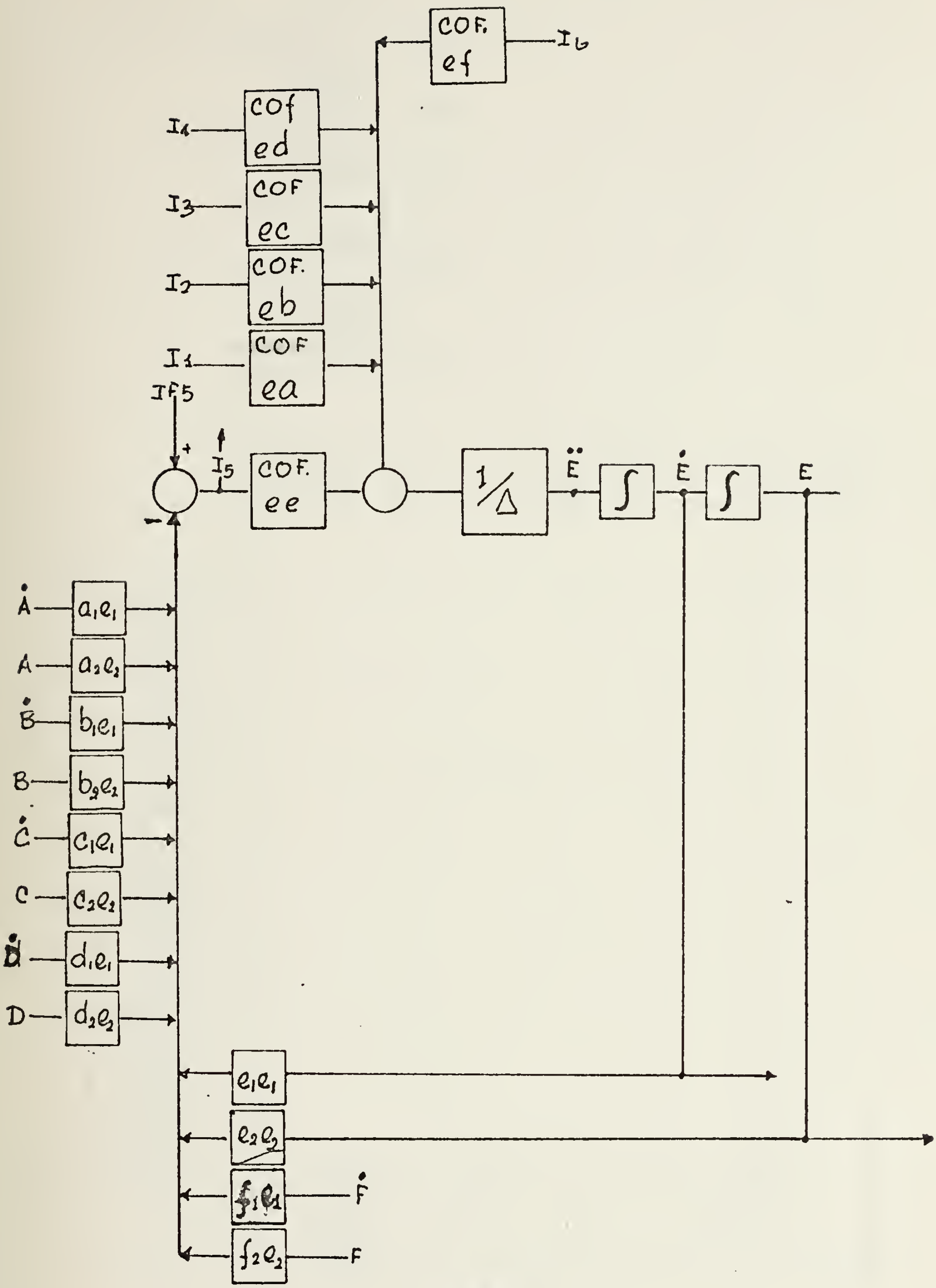

Fig. 2

TRANSFER FUNCTION BLOCK DIAGRAM SIX DEGREES OF FREEDOM(Eqn.E)

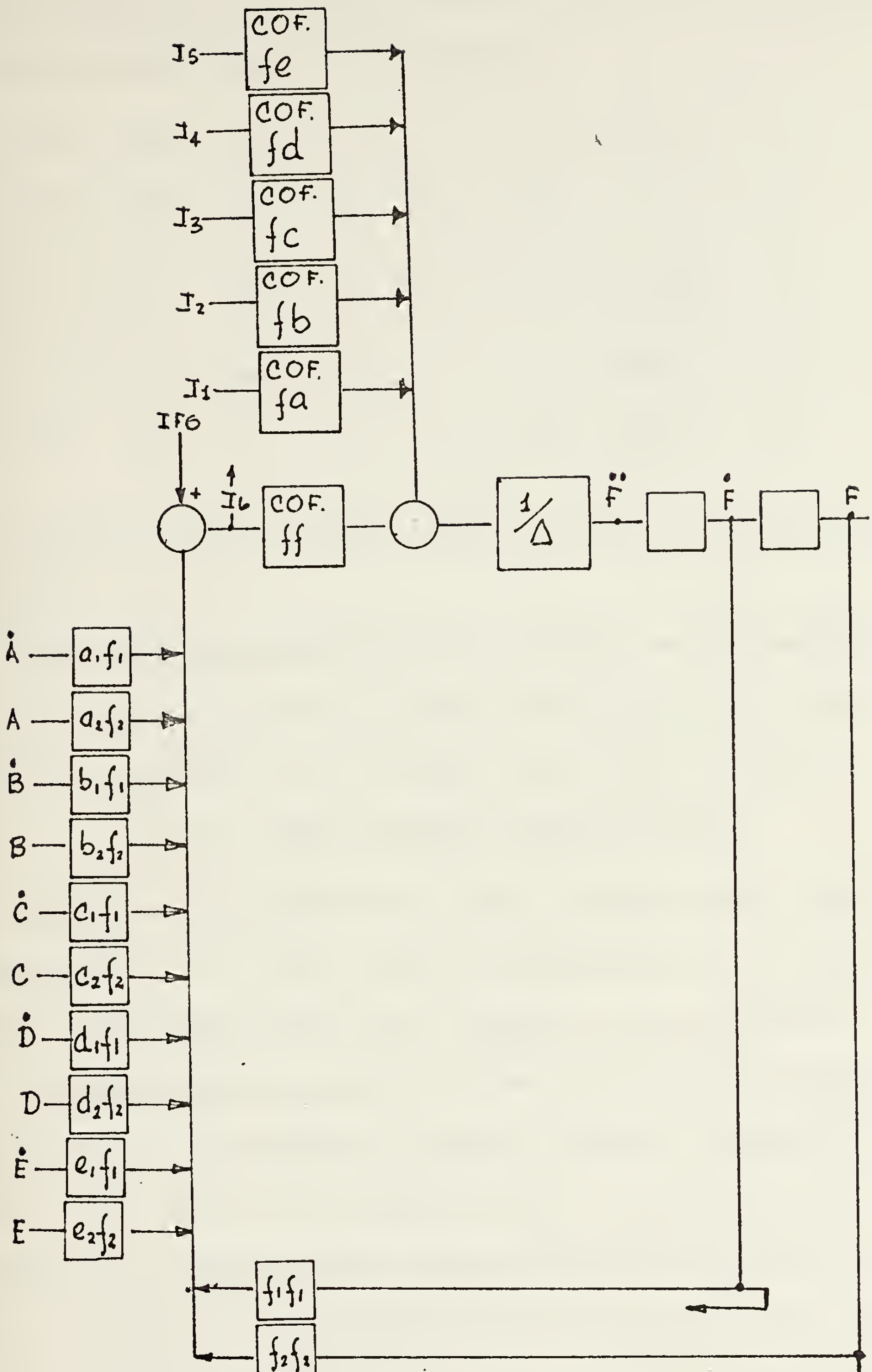

Fig. 2

TRANSFER FUNCTION BLOCK DIAGRAM SIX DEGREES OF FREEDOM(Eqn.F)

are set equal to zero and unused terms on the principal diagonal equal to one, for example :

$$\begin{vmatrix} aa & ba & 0 & 0 & 0 & fa \\ ab & bb & 0 & 0 & 0 & fb \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ af & bf & 0 & 0 & 0 & ff \end{vmatrix} \begin{vmatrix} \ddot{A} \\ \ddot{B} \\ \ddot{C} \\ \ddot{D} \\ \ddot{E} \\ \ddot{F} \end{vmatrix} = \begin{vmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{vmatrix}$$

and the left side of the unused equations are set equal to zero.

With this program non-linear terms can be added such as, rudder deflection of waves and wind, etc., which will be done by adding all of these whose sum is IF_N e.g.

$$1F_1 = KA_1 x\ Dr + KA_2 x\ Ds + KA_3 x\ Db + NA$$

where Dr, Ds and Db are rudder deflection, canard deflection.......... etc. NA is the sum of all non-linear terms that effect the surge equation (X equation).

The program that will be used for solving these equations is the "Continuous Systems Modeling Program" (CSMP) [Ref. 3] in which all constants are declared in the first section and then set the value of matrix for aa, ab, ac .... and so on (in program AAA is used for aa, AAB for ab .... AFF for ff). In the initial section values of the COFACTORS aa, ba....are determined. All of the COFACTORS and the subprogram VALUE is used to compute. This subprogram finds the value of the determinant of the

matrix. For all of the COFACTOR terms the element is set equal to one and the rest of the elements in that row and column are set equal to zero. For example, to find the value of COF.aa the following array is obtained:

$$\text{COF aa} = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & bb & cb & db & eb & fb \\ 0 & bc & cc & dc & ec & fc \\ 0 & bd & cd & dd & ed & fd \\ 0 & be & ce & de & ee & fe \\ 0 & bf & cf & df & ef & ff \end{vmatrix}$$

(In the computer program BAA is used for a_1a_1, GAA for a_2a_2...). After the value of Δ and all cofactors are determined, the dynamic section is used to determine BAA, BAB ......GAA, GAB ...... (if those terms contain variables).

In the dynamic section all variables that are functions of time are determined. The defining relations of the variables are also included in the dynamics section, i.e. UDOT = ADDOT ($\dot{U}=\ddot{A}$), U=ADOT.......etc. XH,YH,ZH are determined and are the vector terms, X,Y,Z whose origin is fixed on the earth (relative to the earth).

III. STUDY OF SHIP "D" PERFORMANCE

In this section the computer will be used to solve the equation of motion describing ship "D". The hydrodynamic coefficients and constants that were obtained from NSRDC (NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER) [Ref. 6] for this study will concern only three degrees of freedom such that SURGE, SWAY, and YAW.

Equations of motion of the ship (nondimensional)

Axial Force

$$
\begin{aligned}
m(\dot{u}-vr+wg) = {} & \frac{\rho}{2}\,\ell(X_{gg}g^2 + X_{rr}r^2 + X_{rp}rp) \\
& + \frac{\rho}{2}\,(X_{\dot{u}}\dot{u} + X_{vr}vr + X_{wg}wg) \\
& + \frac{\rho}{2\ell}(X_{vv}v^2) \\
& + \frac{\rho}{2\ell}\,u^2(X_{\delta r\delta r}\delta r^2+X_{\delta s\delta s}\delta s^2+X_{\delta b\delta b}\delta b^2) \\
& + \frac{\rho}{2\ell}\,(A_1u^2 + A_2u\cdot u_c + A_3u_c^2)\,.
\end{aligned}
$$

Lateral Force

$$
\begin{aligned}
m(\dot{v}+ur-wp) = {} & \frac{\rho}{2}\,\ell(Y_{\dot{p}}\dot{p} + Y_{\dot{r}}\dot{r} + Y_{pq}pq) \\
& + \frac{\rho}{2}\,(Y_{wp}wp+Y_{v|r|}v|r|+uY_rr+Y_{\dot{v}}\dot{v}+uY_pp) \\
& + \frac{\rho}{2}\,(uY_vv + Y_{wv}wv + Y_{|v|v}|v|v) \\
& + \frac{\rho}{2\ell}\,u^2(Y_{\delta r}\delta r)
\end{aligned}
$$

Yawing Moment

$$
\begin{aligned}
I_Z\dot{r} + (I_Y-I_X)pq = {} & \frac{\rho}{2}\,(N_{\dot{r}}\dot{r} + N_{\dot{p}}\dot{p} + N_{pq}pq) \\
& + \frac{\rho}{2\ell}(N_{\dot{v}}\dot{v}+uN_pp+uN_rr+N_{wp}wp+N_{|v|r}|v|r)
\end{aligned}
$$

$$+ \frac{\rho}{2\ell^2}(uN_v v + N_{wv} wv + N_{|v|v}|v|v)$$

$$+ \frac{\rho}{2\ell^2} u^2 (N_{\delta r}\delta r)$$

ρ, the density of fluid is taken as 2 and the terms including w, p. q (heave, roll and pitch) are set equal to zero.

The nonlinear terms such as the squared terms and product terms of v and r are omitted initially. This is in agreement with the small perturbation theory.

After rearranging, the equations become

$$(X_{\dot{u}} - m)\dot{u} = -X_{\delta r \delta r}\delta r^2 \frac{u^2}{\ell}$$

$$(Y_{\dot{v}} - m)\dot{v} + Y_{\dot{r}}\dot{r} = -\frac{u}{\ell} Y_v v - uY_r r - \frac{u^2}{\ell} Y_{\delta r}\delta r$$

$$N_{\dot{v}}\frac{\dot{v}}{\ell} + (N_{\dot{r}} - I_z)\dot{r} = -\frac{u}{\ell^2}N_v v - \frac{u}{\ell^2}N_r r - \frac{u^2}{\ell^2} N_{\delta r}\delta r$$

Set the left side of the equations equal to I_1,---I_6, then the matrix equation becomes

$$\begin{vmatrix} (X_{\dot{u}}-m) & 0 & 0 & 0 & 0 & 0 \\ 0 & (Y_{\dot{v}}-m) & 0 & 0 & 0 & Y_r \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & N_{\dot{v}}/1 & 0 & 0 & 0 & (N_{\dot{r}}-I_z) \end{vmatrix} \begin{vmatrix} \ddot{A} \\ \ddot{B} \\ \ddot{C} \\ \ddot{D} \\ \ddot{E} \\ \ddot{F} \end{vmatrix} \begin{vmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{vmatrix}$$

where $\dot{u} = \ddot{A}$, $\dot{v} = \ddot{B}$, $\dot{r} = \ddot{F}$.

Also set the right side of the equations equal to I_1 ------ I_6

$$
\begin{vmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{vmatrix}
=
\begin{vmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{u}{\ell}Y_v & 0 & 0 & 0 & uY_r \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{u}{\ell^2}N_v & 0 & 0 & 0 & \frac{u}{\ell}N_r
\end{vmatrix}
\begin{vmatrix} \dot{A} \\ \dot{B} \\ \dot{C} \\ \dot{D} \\ \dot{E} \\ \dot{F} \end{vmatrix}
$$

$$
+ \begin{vmatrix} \\ \\ & \text{All Zero} & \\ \\ \\ \end{vmatrix}
\begin{vmatrix} A \\ B \\ C \\ D \\ E \\ F \end{vmatrix}
+
\begin{vmatrix} IF1 \\ IF2 \\ IF3 \\ IF4 \\ IF5 \\ IF6 \end{vmatrix}
$$

where $u = \dot{A}$, $v = \dot{B}$, $r = \dot{F}$, and $IF1 = -X_{\delta r \delta r} \delta r^2 \frac{u^2}{\ell}$

$IF2 = -Y_{\delta r} \delta r \frac{u^2}{\ell}$

$IF3 = 0$

$IF4 = 0$

$IF5 = 0$

$IF6 = -N_{\delta r} \delta r \frac{u^2}{\ell^2}$

A. NONLINEAR TERMS NOT INCLUDED

TABLE I

Hydrodynamic Coefficients and Constants of Ship "D" for Linear Terms (Non-dimensional)

$$m = 0.0045$$

$$Iz = 0.0003$$

$$Nr = 0.0012$$

$$Nr = -0.0002$$

$$Nv = -0.0012$$

$$Nv = -0.0001$$

$$Xu = -0.00036$$

$$Yv = -0.0025$$

$$Yv = -0.0063$$

$$Yr = 0.004$$

$$X_{\delta r\delta r} = -0.0011$$

$$Y_{\delta r} = 0.0019$$

$$N_{\delta r} = -0.00084$$

δs and δb equal zero

In the computer program, set all coefficients in section 1 and set AAA = $X\dot{u}-m$, AAB = 0 ---- AFF = $N\dot{r}-Iz$. After this, use subprogram value to find the determinant and coefficient of AA, BB ---- and then set BBB = $\frac{u}{\ell}$ Yv , BFB = uYr ------- BFF = $\frac{u}{\ell}$ Nr .

$$IF1 = KA1\delta r \quad \text{where } KA1 = -X_{\delta r\delta r}\delta r\,\frac{u^2}{\ell}$$

$$IF2 = KB1\delta r \quad \text{where } KB2 = -Y_{\delta r}\, u^2/\ell$$

$$IF3 = KF1\delta r \quad \text{where } KF1 = -N_{\delta r}\, u^2/\ell^2$$

Following is the program that used CSMP to determine the turning circles for rudder angles of 15^{o}(-0.2619 rad.), 25^{o}(-0.4365 rad.) and 35^{o}(-0.6111 rad.). Result of this study is presented in Fig. 3. The turning rate as a function of time is interested and the results of this analysis are presented in Fig. 4. The ships turning performance expressed in transfer ship lengths as time is shown in Fig. 5 and the heading angle as a function of time is given in Fig. 6. Fig. 7 shows the results of the zig-zag maneuver, curve shown the yaw angle and rudder angle in degree as a function of time, for this study the same program was used, but set DR in dynamic section:

```
DR= -0.06984(RAMP(0.0)-RAMP(5.0))+0.04656(RAMP(40.0)...
    -RAMP(65.0)-RAMP(145.0)+RAMP(170.0)+RAMP(250.0)....
    -RAMP(265.0)-RAMP(345.0)+RAMP(425.0)+RAMP(440.0))
```

and use prepare statement prepare X, YAWD and prepare X, DOO (YAWD = YAW* 57.273, DOO = DR* 57.273).

```
                    COMPUTER PROGRAM 1
 SURFACE SHIP IN THREE DEGREES OF FREEDOM(NON LINEAR TERMS NOT INCLUDED)
*THIS PROGRAM SIMULATES THE DYNAMICS OF A SHIP IN 6 DEGREES OF FREEDOM
*THE EQUATIONS OF MOTION ARE ASSUMED TO BE IN THE FORM:
*  HAA*A+HBA*B+HCA*C+HDA*D+HEA*E+HFA*F=IFA
*  HAB*A+HBB*B+HCB*C+HDB*D+HEB*E+HFB*F=IFB
*  HAC*A+HBC*B+HCC*C+HDC*D+HEC*E+HFC*F=IFC
*  HAD*A+HBD*B+HCD*C+HDD*D+HED*E+HFD*F=IFD
*  HAE*A+HBE*B+HCE*C+HDE*D+HEE*E+HFE*F=IFE
*  HAF*A+HBF*B+HCF*C+HDF*D+HEF*E+HFF*F=IFF
*HIJ ARE POLYNOMIALS OF THE FORM:AIJ*S**2+BIJ*S+GIJ
*WHERE I IS THE COLUMN AND J IS THE ROW
*A,B,C,D,E,F ARE THE VARIABLES
*  IFJ=KJ1*D1+KJ2*D2+NJ
*AIJ,BIJ,GIJ,HJ1,KJ# MUST BE DEFINED IN SECTION 2 FROM THE HYDRODYNAMIC
*COEFFICIENTS AND THE NONDIMENSIONALIZATION PROCESS.
*THE VALUES FOR AIJ MUST BE DEFINED AS INDICATED IN SECTION 2A
*IF NOT ALL EQUATIONS ARE USED,THE NON USED AIJ MUST BE SET=1
*THIS SITUATION CAN ARISE WHEN ONLY THE LATERAL OR LONGITUDINAL DYN.IS DESIRED
*NON USED  TERMS ARE SET AUTOMATICALLY TO ZERO BY THE SORT SECTION
*OF THE SYSTEM, UP TO A MAXIMUM OF 85.THE EXCESS  MUST BE DECLARED IN
*SECTION 2
*D1,D2 ARE THE DEFLECTIONS OF RUDDERS,CANARDS ETC
*NJ ARE TERMS IN WHICH CAN BE INCLUDED THE COMPONENTS OF FORCES AND MOMENTS
*DUE TO WAVES AND/OR WIND.ALSO NON LINEAR TERMS CAN BE DEFINED BUT UP TO
*THE FIRST DERIVATIVE OF THE BASIC VARIABLES(A,B,C,D,E,F).IF OTHER  EFFECTS OR
*MORE RUDDERS ,CANARDS ETC. ARE REQUIRED THEY CAN ALSO BE INCLUDED IN IFJ
*ALL DEFINITIONS   CAN BE   INCLUDED IN SECTION 3.NO ORDER REQUIRED
*HYDRODYNAMICS COEFFICIENTS AND OTHER PARAMETERS ARE INTRODUCED IN SECTION 1
*
*THE VARIABLES A,B,.... THEIR FIRST DERIVATIVES ADOT,BDOT,.... AND
*THEIR SECOND DERIVATIVES ADDOT,BDDOT.... ARE AVAILABLE TO PRINT-PLOT
*
*THE DETERMINANT AND COFACTORS ARE PRINTED;COFOO=DEL,COF11=COFAA,COF21=COFAB...
*
*THE PARAMETERS:M,M2,M1,K,L,N,LP1,KP,J,I DEFINED AS FIXED CAN NOT BE USED
*SINCE THEY ARE PART OF THE MAIN SIMULATION
FIXED M,M2,M1,K,L,N,LP1,KP,J,I
*SECTION 1 -COEFFICIENTS FOR A PARTICULAR SHIP
TITLE SURFACE SHIP 3 DEGREE OF FREEDOM
INCON ADOTO=0.04263
PARAM UC=0.04263
PARAM DR=-0.2619
PARAM XDRDR=-0.0011
PARAM YDR=0.0019
PARAM NDR=-0.00084
PARAM XUDOT=-0.00036
PARAM ML=0.0045
```

```
PARAM YVDOT=-C.0025
PARAM YV=-0.0063
PARAM LC=1.0
PARAM YRDCT=-C.0C02
PARAM YR=0.004
PARAM NVDCT=-C.0C01
PARAM NRDOT=-C.C002
PARAM IZ=0.0003
PARAM NV=-0.0C12
PARAM NR=-0.0012
PARAM XL=-0.0012
PARAM KA2=0.
PARAM KA3=0.
PARAM KB2=0.
PARAM KB3=0.
PARAM KC1=0.
PARAM KC2=0.
PARAM KC3=0.
PARAM KD2=0.
PARAM KD3=0.
PARAM KE1=0.0
PARAM KE2=0.
PARAM KE3=0.
*SECTICN 2 -PARAMETERS CALCULATIONS
INITIAL
*SECTION 2A -ALL PARAMETERS MUST BE DEFINED ANC IN SEQUENCE:
*AAA,AAB,AAC,AAD,AAE,AAF,ABA,ABB,ABC,ABD,ABE,ABF,ACA,ACB,ACC,ACD,ACE
*ACF,ADA,ADB,ADC,ADD,ADE,ADF,AEA,AEB,AEC,AED,AEE,AEF,AFA,AFB,AFC,AFD,AFE,AFF
      AAA=XUDOT-ML
      AAB=0.
      AAC=0.
      AAD=0.
      AAE=0.
      AAF=0.
      ABA=0.
      ABB=YVDOT-ML
      ABC=0.
      ABD=0.0
      ABE=0.
      ABF=NVDOT/LC
      ACA=0.
      ACB=0.
      ACC=1.0
      ACD=0.
      ACE=0.
      ACF=0.
      ADA=0.0
      ADB=0.0
```

```
      ACC=0.
      ACD=1.0
      ACE=0.
      ACF=0.0
      AEA=0.
      AEB=0.
      AEC=0.
      AED=0.
      AEE=1.0
      AEF=0.
      AFA=0.
      AFB=LC*YRDOT
      AFC=0.
      AFD=0.0
      AFE=0.
      AFF=NRDOT-IZ
*END SECTION 2A
      CEL=VALUE(AAA,0,0)
      CCFAA=VALUE(AAA,1,1)
      CCFAB=VALUE(AAA,2,1)
      CCFAC=VALUE(AAA,3,1)
      CCFAD=VALUE(AAA,4,1)
      CCFAE=VALUE(AAA,5,1)
      CCFAF=VALUE(AAA,6,1)
      CCFBA=VALUE(AAA,1,2)
      CCFBB=VALUE(AAA,2,2)
      CCFBC=VALUE(AAA,3,2)
      CCFBD=VALUE(AAA,4,2)
      CCFBE=VALUE(AAA,5,2)
      CCFBF=VALUE(AAA,6,2)
      CCFCA=VALUE(AAA,1,3)
      CCFCB=VALUE(AAA,2,3)
      CCFCC=VALUE(AAA,3,3)
      CCFCD=VALUE(AAA,4,3)
      CCFCE=VALUE(AAA,5,3)
      CCFCF=VALUE(AAA,6,3)
      CCFDA=VALUE(AAA,1,4)
      CCFDB=VALUE(AAA,2,4)
      CCFDC=VALUE(AAA,3,4)
      CCFDD=VALUE(AAA,4,4)
      CCFDE=VALUE(AAA,5,4)
      CCFDF=VALUE(AAA,6,4)
      CCFEA=VALUE(AAA,1,5)
      CCFEB=VALUE(AAA,2,5)
      CCFEC=VALUE(AAA,3,5)
      CCFED=VALUE(AAA,4,5)
      CCFEE=VALUE(AAA,5,5)
      CCFEF=VALUE(AAA,6,5)
```

```
      COFFA=VALUE(AAA,1,6)
      COFFB=VALUE(AAA,2,6)
      COFFC=VALUE(AAA,3,6)
      COFFD=VALUE(AAA,4,6)
      COFFE=VALUE(AAA,5,6)
      COFFF=VALUE(AAA,6,6)
DYNAMIC
      DCC=-DR*57.273
      X=TIME
      KA1=-XDRDR*U*U*DR/LC
      KB1=-YDR*U*U/LC
      KC1=-KDR*U*U/LC**2
      KF1=-NDR*U*U/LC**2
      BBB=U*YV/LC
      BBC=U*KV/LC**2
      BBF=U*NV/LC**2
      BCB=U*YP
      BCC=U*KPC/LC
      BCF=U*NP/LC
      BFB=U*YR
      BFC=U*KR/LC
      BFF=U*NR/LC
*SECTION 3-DEFINITIONS
      UDOT=ADDOT
      U=ADOT
      VDOT=BDDOT
      V=BDOT
      WDOT=CDDOT
      W=CDOT
      PDOT=DDDOT
      P=DDOT
      QDOT=EDDOT
      Q=EDOT
      RDOT=FDDOT
      R=FDOT
      D1=DR
      D2=DS
      D3=DB
      ABR=ABS(R)
      ABV=ABS(V)
      ABQ=ABS(Q)
      ABW=ABS(W)
      ABP=ABS(P)
*KINEMATIC RELATIONS
      RODOT=P+YADOT*SIN(PITCH)
      PIDOT=Q*COS(ROLL)-R*SIN(ROLL)
      YADOT=(R+PIDOT*SIN(ROLL))/COS(PITCH)*COS(ROLL)
      YAWRD=YADOT*57.273
```

```
      ROLL=INTGRL(0.,RODOT)
      PITCH=INTGRL(0.,PIDOT)
      YAW=INTGRL(0.,YADOT)
      YAWD=YAW*57.273
      XHDOT=U*COS(YAW) - V*SIN(YAW)
      YHDOT=U*SIN(YAW)+V*COS(YAW)
      XVDOT=U*COS(PITCH)+W*SIN(PITCH)
      ZVDOT=-U*SIN(PITCH)+W*COS(PITCH)
      XH=INTGRL(0.,XHDOT)
      YH=INTGRL(0.,YHDOT)
      XV=INTGRL(0.,XVDOT)
      ZV=INTGRL(C00.,ZVDOT)
*SECTION 4 -PROGRAMMED SYMULATION
      I1=-BAA*ADOT-GAA*A-BBA*BDOT-GBA*B-BCA*CDOT-GCA*C...
      -BDA*DDOT-GDA*D-BEA*EDOT-GEA*E-BFA*FDOT-GFA*F+IF1
      I2=-BAB*ADOT-GAB*A-BBB*BDOT-GBB*B-BCB*CDOT-GCB*C...
      -BDB*DDOT-GDB*D-BEB*EDOT-GEB*E-BFB*FDOT-GFB*F+IF2
      I3=-BAC*ADOT-GAC*A-BBC*BDOT-GBC*B-BCC*CDOT-GCC*C...
      -BDC*DDOT-GDC*D-BEC*EDOT-GEC*E-BFC*FDOT-GFC*F+IF3
      I4=-BAD*ADOT-GAD*A-BBD*BDOT-GBD*B-BCD*CDOT-GCD*C...
      -BDD*DDOT-GDD*D-BED*EDOT-GED*E-BFD*FDOT-GFD*F+IF4
      I5=-BAE*ADOT-GAE*A-BBE*BDOT-GBE*B-BCE*CDOT-GCE*C...
      -BDE*DDOT-GDE*D-BEE*EDOT-GEE*E-BFE*FDOT-GFE*F+IF5
      I6=-BAF*ADOT-GAF*A-BBF*BDOT-GBF*B-BCF*CDOT-GCF*C...
      -BDF*DDOT-GDF*D-BEF*EDOT-GEF*E-BFF*FDOT-GFF*F+IF6
      IF1=KA1*D1+KA2*D2+KA3*D3+NA
      IF2=KB1*D1+KB2*D2+KB3*D3+NB
      IF3=KC1*D1+KC2*D2+KC3*D3+NC
      IF4=KD1*D1+KD2*D2+KD3*D3+ND
      IF5=KE1*D1+KE2*D2+KE3*D3+NE
      IF6=KF1*D1+KF2*D2+KF3*D3+NF
      ADDOT=(COFAA*I1+COFAB*I2+COFAC*I3+COFAD*I4+COFAE*I5+COFAF*I6)/DEL
      BDDOT=(COFBA*I1+COFBB*I2+COFBC*I3+COFBD*I4+COFBE*I5+COFBF*I6)/DEL
      CDDOT=(COFCA*I1+COFCB*I2+COFCC*I3+COFCD*I4+COFCE*I5+COFCF*I6)/DEL
      DDDOT=(COFDA*I1+COFDB*I2+COFDC*I3+COFDD*I4+COFDE*I5+COFDF*I6)/DEL
      EDDOT=(COFEA*I1+COFEB*I2+COFEC*I3+COFED*I4+COFEE*I5+COFEF*I6)/DEL
      FDDOT=(COFFA*I1+COFFB*I2+COFFC*I3+COFFD*I4+COFFE*I5+COFFF*I6)/DEL
      ADOT=INTGRL(ADOTO,ADDOT)
      BDOT=INTGRL(0.,BDDOT)
      CDOT=INTGRL(0.,CDDOT)
      DDOT=INTGRL(0.,DDDOT)
      EDOT=INTGRL(0.,EDDOT)
      FDOT=INTGRL(0.,FDDOT)
      A=INTGRL(0.,ADOT)
      B=INTGRL(0.,BDOT)
      C=INTGRL(0.,CDOT)
      D=INTGRL(0.,DDOT)
      E=INTGRL(0.,EDOT)
```

```
      F=INTGRL(C.,FDOT)
*SECTICN 5 -OUTPUT CHARACTERISTICS
 TIMER DELT=0.01,FINTIM=240.0,CUTDEL=1.0,PRDEL=1.C
      PREPARE YH,XH
 ENC
PARAM CR=-0.4365
ENC
PARAM CR=-0.6111
END
STCP


      FUNCTION VALUE(Y,I,M)
CCMMCN
      CIMENSICN X(6,6),Y(6,6)
      DC 1 M1=1,6
      DC 1 M2=1,6
    1  X(M1,M2)=Y(M1,M2)
      IF(I.EQ.C) GO TO 1CC
      X(I,1)=0.
      X(I,2)=0.
      X(I,3)=C.
      X(I,4)=0.
      X(I,5)=C.
      X(I,6)=C.
      X(1,M)=0.
      X(2,M)=C.
      X(3,M)=0.
      X(4,M)=0.
      X(5,M)=C.
      X(6,M)=0.
      X(I,M)=1.
  1CC CCNTINUE
      WRITE(6,49) I,M
   49 FCRMAT(/,' ','DETERMINANT FCR CCF',I1,I1,':')
      DO 50 M1=1,6
      WRITE(6,51)(X(M1,M2),M2=1,6)
   51 FCRMAT(1C(1X,E13.6))
   5C CCNTINUE
      N=6
      DE=1.DC
   1C  DC 34 L=1,N
       KP=0
       Z=C.0
       DC 12 K=L,N
      IF(Z-ABS(X(K,L)))11,12,12
   11 Z=ABS(X(K,L))
       KP=K
```

```
12   CCNTINUE
     IF(L-KP)13,20,20
13   CC 14 J=L,N
     Z=X(L,J)
     X(L,J)=X(KP,J)
14   X(KP,J)=Z
    CC=-DD
20   IF(L-N)31,40,40
31   LP1=L+1
     CC 34 K=LP1,N
     IF(X(K,L))32,34,32
32   RATIO=X(K,L)/X(L,L)
     CO 33 J=LP1,N
33   X(K,J)=X(K,J)-RATIC*X(L,J)
34   CCNTINUE
4C  CC 41 K=1,N
41  CC=DD*X(K,K)
    D=DD
    VALUE=D
    WRITE(6,52) I,M,VALUE
52  FCRMAT(' ','COF',I1,I1,'=',E15.6)
    RETURN
    END
ENDJCB
```

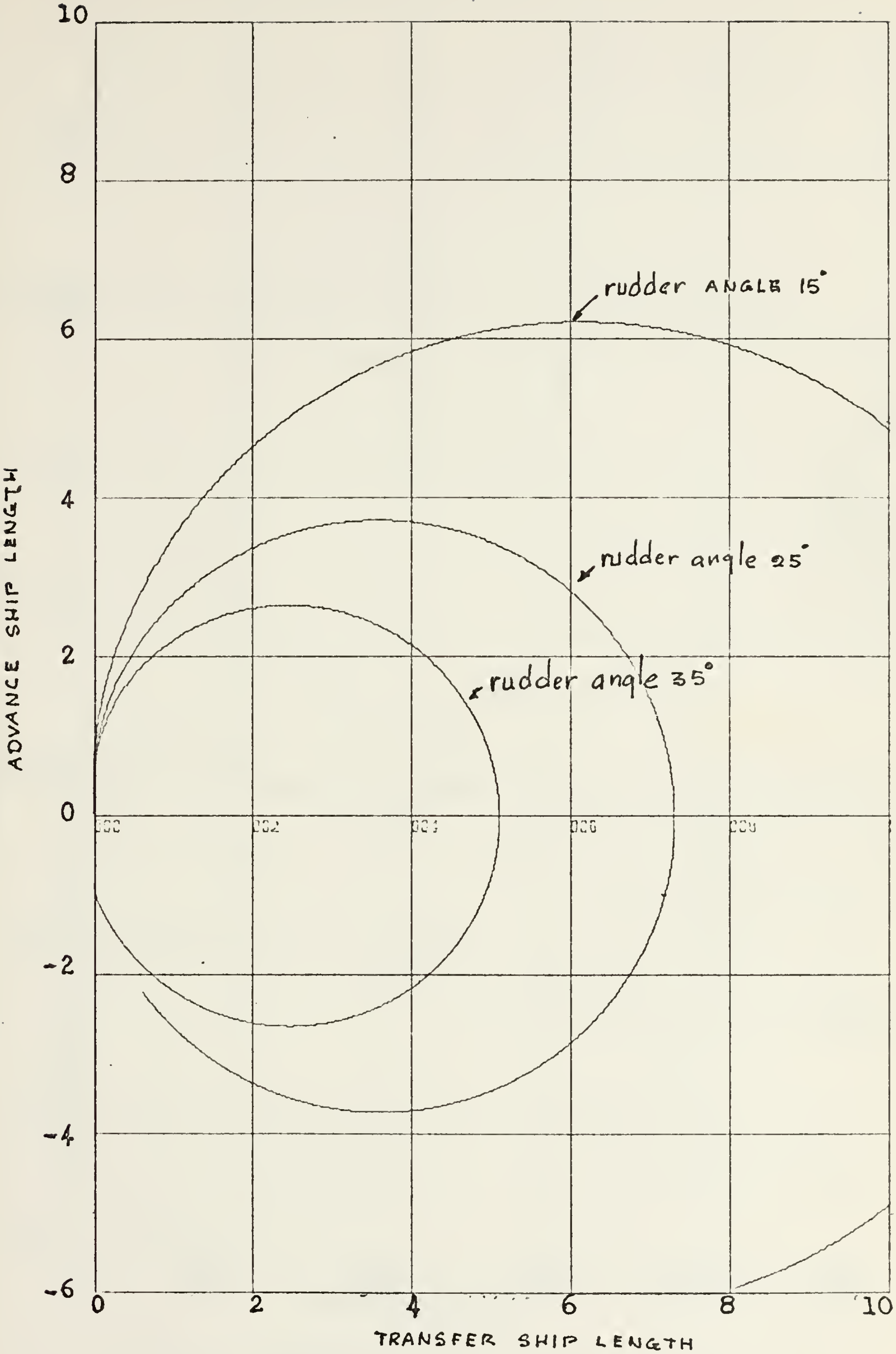

FIG. 3 ADVANCE VS. TRANSFER SHIP LENGTH
(RUDDER 15°, 25° & 35°)

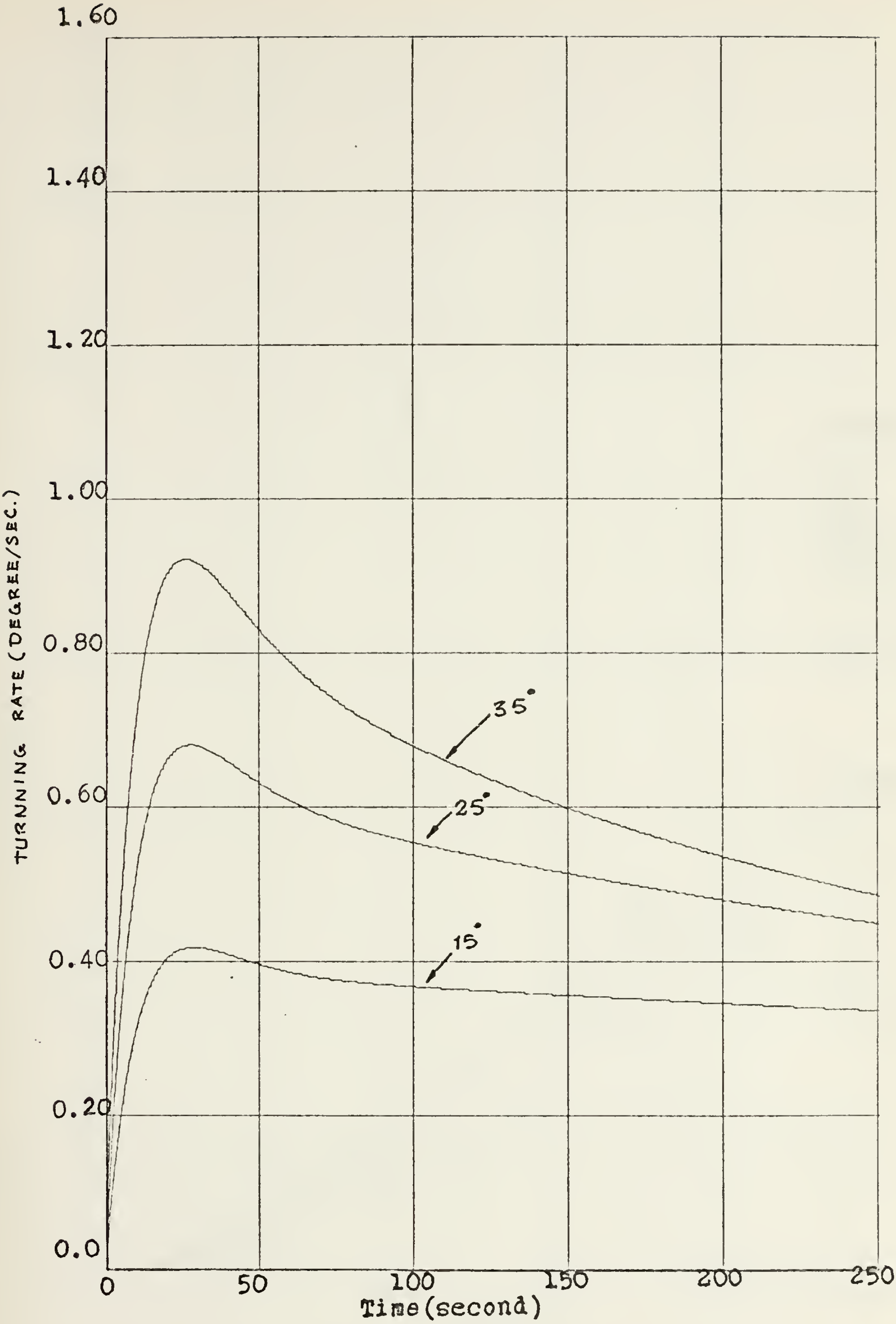

FIG. 4 TURNNING RATE VS. TIME
(RUDDER 15°, 25°, 35°)

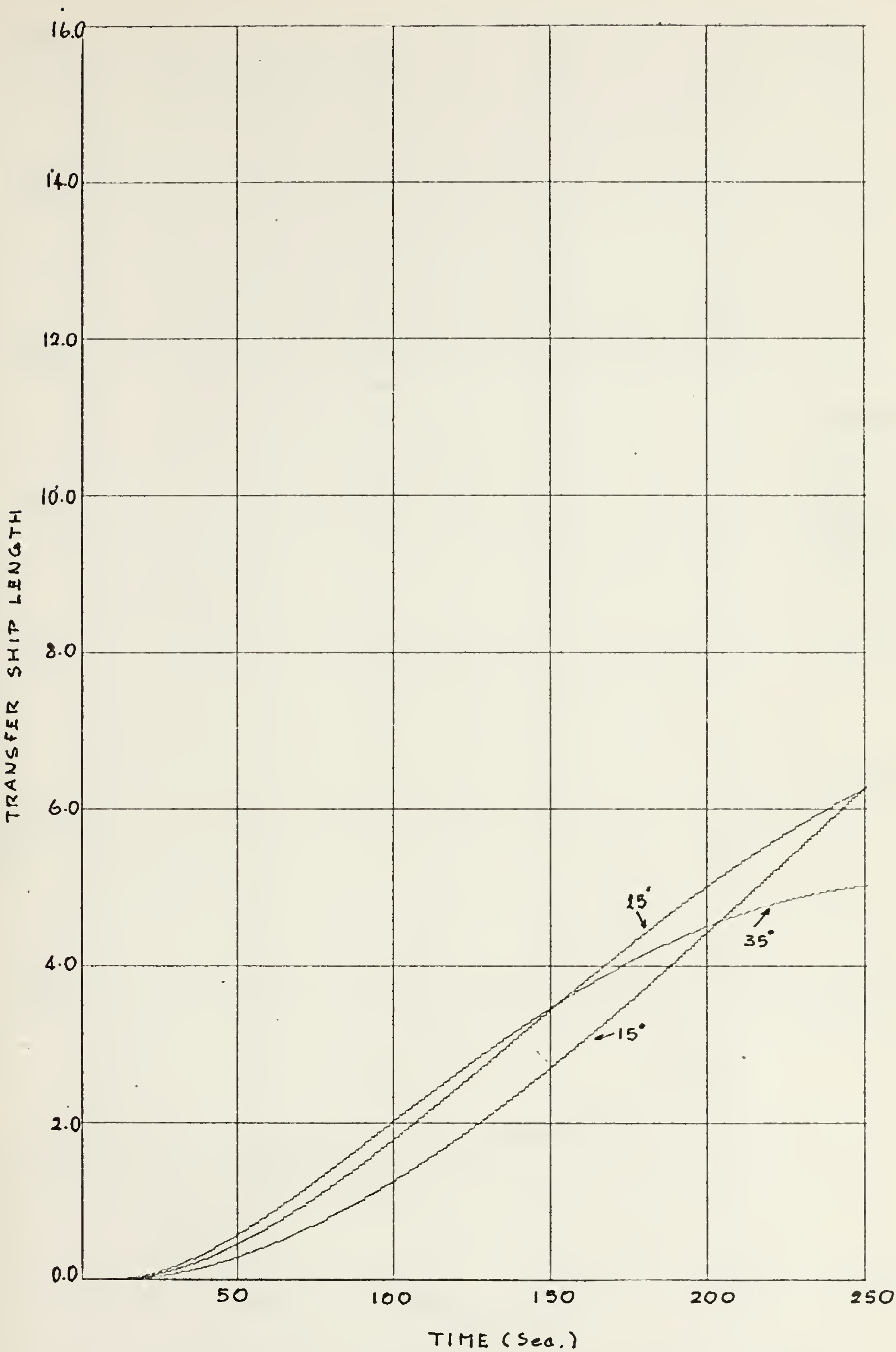

FIG. 5 TRANSFER SHIP LENGTH VS. TIME
(RUDDER ANGLE 15°, 25°, 35°)

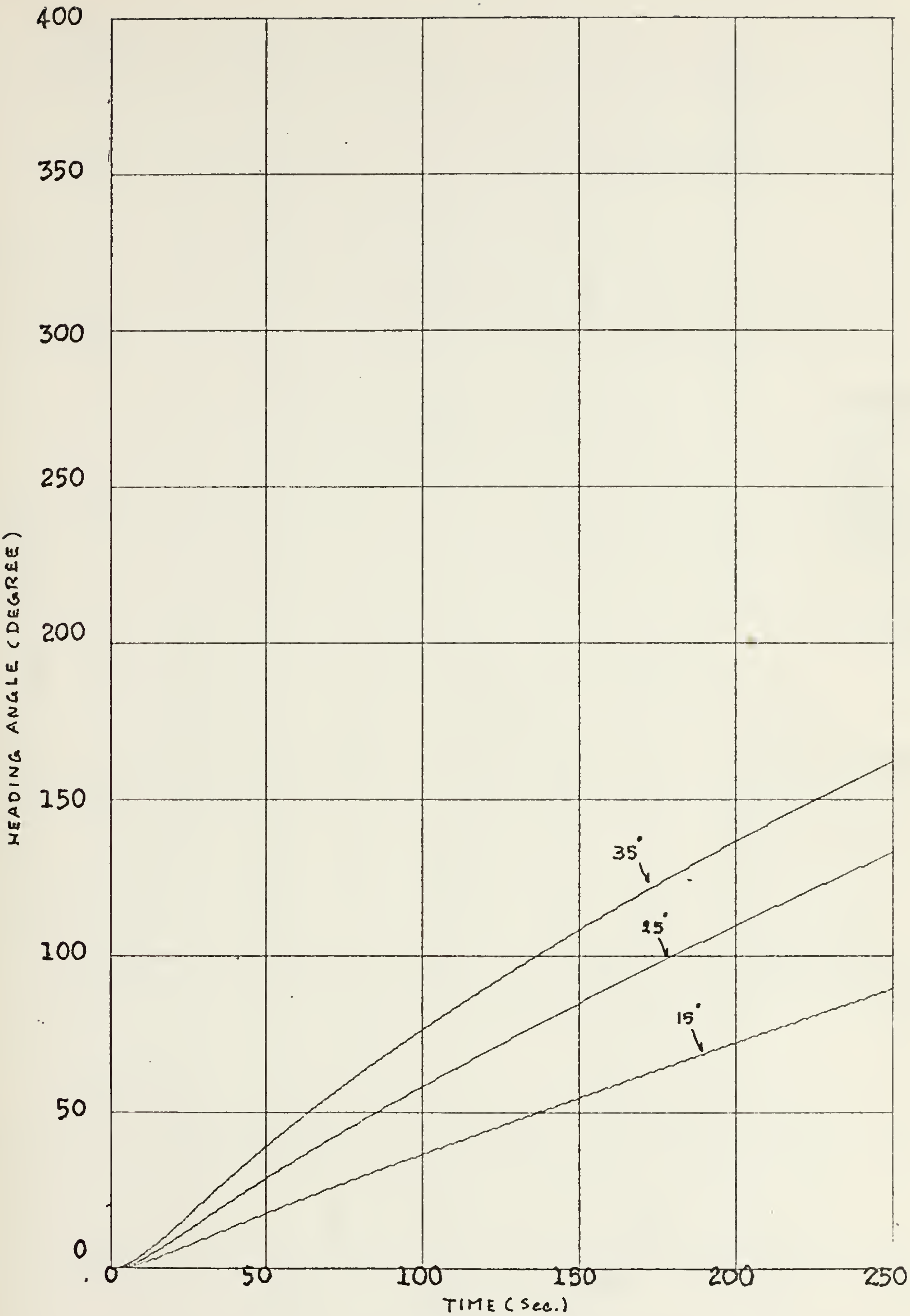

FIG. 6 HEADING ANGLE AS FUNCTION OF TIME
(RUDDER ANGLE 15°, 25° & 35°)

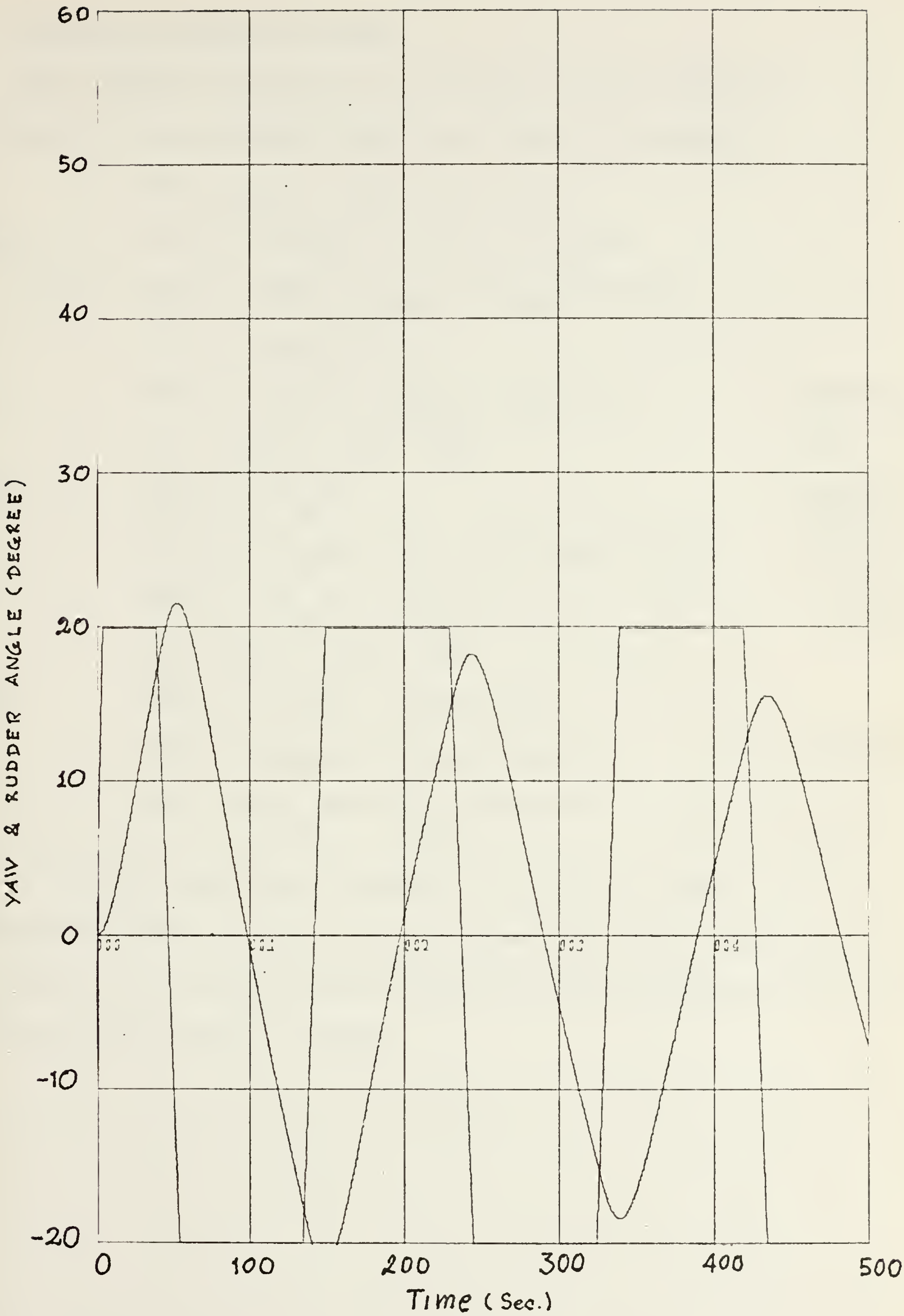

Fig. 7 YAW & RUDDER ANGLE VS. TIME ZIG-ZAG MANOEUVER

B. INCLUDED NONLINEAR TERMS

The computer program 2 is the same as the computer program 1, but nonlinear terms are added by setting:

$$NA = NA1 + NA2 + NA3 + NA4$$

where $NA1 = -1(X_{qq}q^2 + X_{rr}r^2 + X_{rp}rp)$

$$NA2 = -(mvr + X_{vr}vr + X_{wq}wq + mwq)$$

$$NA3 = -(X_{vv}v^2)/1$$

$$NA4 = -(A1u^2 + A2uu_c + A3u_c^{\ 2})/1$$

$$NB = NB1 + NB2 + NB3$$

where $NB1 = -1Y_{pq}pq$

$$NB2 = -(Y_{wp}wp + Y_{v|r|}v|r| + mur + mwp)$$

$$NB3 = -(Y_{wv}wv + Y_{|v|v}|v|v)/1$$

$$NF = NF1 + NF2 + NF3$$

where $NF1 = -N_{pq}pq + (Iy-Ix)\ pq$

$$NF2 = -(N_{wp}wp + N_{|v|r}|v|r)/1$$

$$NF3 = -(N_{wv}wv + N_{|v|v}|v|v)/1^2$$

Again setting terms that include w, p, and q (heave, roll and pitch) equal to zero, and set number of known terms from Table II into section 1 of CSMP program (unknown co-efficients set equal to zero).

TABLE II

Hydrodynamic Coefficients of Ship "D" for Nonlinear Terms (non-dimensional)

$X_{rr} = 0.00005$

$X_{vr} = 0.00241$

$X_{vv} = -0.00341$

$Y_{v|v|} = -0.0416$

$N_{v|v|} = -0.01002$

PROPULSION RATIO $\triangleq \eta$

	$\eta \geq 0.45$	$-1.0 \leq \eta < 0.45$	$\eta \leq 1.0$
A1	-0.00004	-0.00032	-0.00117
A2	-0.00035	0.00070	-0.00100
A3	0.00099	0	-0.00085

Fig. 8 - Fig. 12 are the same results as Fig. 3 - Fig. 7. The results of computer program 2 are more accurate than the computer program 1, when compared with free running model test of NSRDC [Ref. 6]. Fig. 13 and Fig. 14 when studying the stability of the ship by applying a force moment to the ship in computer program, set

NF1 0.0001*(STEP(10.0)-STEP(10.01)) (can use NF1 be-l ause NF1 in this program equal zero)

Study direction stability of the ship by plotting direction of the ship (used advance VS. transfer ship length)and check heading angle of the ship by plotting YAW VS. TIME.

```
                          COMPUTER PROGRAM 2
 SURFACE SHIP IN THREE DEGREES OF FREDOM(INCLUDED NON LINEAR TERMS)
*THIS PROGRAM SIMULATES THE DYNAMICS OF A SHIP IN 6 DEGREES OF FREEDOM
*THE EQUATIONS OF MOTION ARE ASSUMED TO BE IN THE FORM:
*  HAA*A+HBA*B+HCA*C+HDA*D+HEA*E+HFA*F=IFA
*  HAB*A+HBB*B+HCB*C+HDB*D+HEB*E+HFB*F=IFB
*  HAC*A+HBC*B+HCC*C+HDC*D+HEC*E+HFC*F=IFC
*  HAD*A+HBD*B+HCD*C+HDD*D+HED*E+HFD*F=IFD
*  HAE*A+HBE*B+HCE*C+HDE*D+HEE*E+HFE*F=IFE
*  HAF*A+HBF*B+HCF*C+HDF*D+HEF*E+HFF*F=IFF
*HIJ ARE POLYNOMIALS OF THE FORM:AIJ*S**2+BIJ*S+GIJ
*WHERE I IS THE COLUMN AND J IS THE ROW
*A,B,C,D,E,F ARE THE VARIABLES
*  IFJ=KJ1*D1+KJ2*D2+NJ
*AIJ,BIJ,GIJ,HJ1,KJ# MUST BE DEFINED IN SECTION 2 FROM THE HYDRODYNAMIC
*COEFFICIENTS AND THE NONDIMENSIONALIZATION PROCESS.
*THE VALUES FOR AIJ MUST BE DEFINED AS INDICATED IN SECTION 2A
*IF NOT ALL EQUATIONS ARE USED,THE NON USED AIJ MUST BE SET=1
*THIS SITUATION CAN ARISE WHEN ONLY THE LATERAL OR LONGITUDINAL DYN.IS DESIRED
*NON USED  TERMS ARE SET AUTOMATICALLY TO ZERO BY THE SORT SECTION
*OF THE SYSTEM, UP TO A MAXIMUM OF 85.THE EXCESS  MUST BE DECLARED IN
*SECTION 2
*D1,D2 ARE THE DEFLECTIONS OF RUDDERS,CANARDS ETC
*NJ ARE TERMS IN WHICH CAN BE INCLUDED THE COMPONENTS OF FORCES AND MOMENTS
*DUE TO WAVES AND/OR WIND.ALSO NON LINEAR TERMS CAN BE DEFINED BUT UP TO
*THE FIRST DERIVATIVE OF THE BASIC VARIABLES(A,B,C,D,E,F).IF OTHER  EFFECTS OR
*MORE RUDDERS ,CANARDS ETC. ARE REQUIRED THEY CAN ALSO BE INCLUDED IN IFJ
*ALL DEFINITIONS   CAN BE   INCLUDED IN SECTION 3.NO ORDER REQUIRED
*HYDRODYNAMICS COEFFICIENTS AND OTHER PARAMETERS ARE INTRODUCED IN SECTION 1
*
*THE VARIABLES A,B,.... THEIR FIRST DERIVATIVES ADOT,BDOT,.... AND
*THEIR SECOND DERIVATIVES ADDOT,BDDOT.... ARE AVAILABLE TO PRINT-PLOT
*
*THE DETERMINANT AND COFACTORS ARE PRINTED;COF00=DEL,COF11=COFAA,COF21=COFAB...
*
*THE PARAMETERS:M,M2,M1,K,L,N,LP1,KP,J,I DEFINED AS FIXED CAN NOT BE USED
*SINCE THEY ARE PART OF THE MAIN SIMULATION
FIXED M,M2,M1,K,L,N,LP1,KP,J,I
*SECTION 1 -COEFFICIENTS FOR A PARTICULAR SHIP
TITLE SURFACE SHIP 3 DEGREE OF FREEDOM
INCON ADOTC=0.04263
PARAM UC=0.04263
PARAM DR=-0.2619
PARAM XDRDR=-0.0011
PARAM YDR=0.0019
PARAM NDR=-0.00084
PARAM XUDOT=-0.00036
PARAM ML=0.0045
```

```
PARAM YVDOT=-0.0025
PARAM YV=-0.0063
PARAM LC=1.0
PARAM YRDOT=-0.0002
PARAM YR=0.004
PARAM NVDOT=-0.0001
PARAM NRDOT=-0.0002
PARAM IZ=0.0003
PARAM NV=-0.0012
PARAM NR=-0.0012
PARAM XU=-0.0012
PARAM KA2=0.
PARAM KA3=0.
PARAM KB2=0.
PARAM KB3=0.
PARAM KC1=0.
PARAM KC2=0.
PARAM KC3=0.
PARAM KD2=0.
PARAM KD3=0.
PARAM KE1=0.0
PARAM KE2=0.
PARAM KE3=0.
PARAM XRR=0.00005
PARAM XVR=0.00241
PARAM XVV=-0.00341
PARAM A1=-0.00032
PARAM A2=0.0007
PARAM A3=0.0
PARAM Y1V1V=-0.0416
PARAM N1V1V=-0.01002
PARAM XQQ=0.
PARAM XRP=0.
PARAM XWQ=0.
PARAM YPQ=0.
PARAM YWP=0.
PARAM YV1R1=0.
PARAM YWV=0.
PARAM NPQ=0.
PARAM NWP=0.
PARAM N1V1R=0.
PARAM NWV=0.
PARAM NC=0.
*SECTION 2 -PARAMETERS CALCULATIONS
INITIAL
*SECTION 2A -ALL PARAMETERS MUST BE DEFINED AND IN SEQUENCE:
*AAA,AAB,AAC,AAD,AAE,AAF,ABA,ABB,ABC,ABD,ABE,ABF,ACA,ACB,ACC,ACD,ACE
*ACF,ADA,ADB,ADC,ADD,ADE,ADF,AEA,AEB,AEC,AED,AEE,AEF,AFA,AFB,AFC,AFD,AFE,AFF
```

```
      W=CDOT
      PDOT=DDDOT
      P=DDOT
      QDOT=EDDOT
      Q=EDOT
      RDOT=FDDOT
      R=FDOT
      D1=DR
      D2=DS
      D3=DB
      ABR=ABS(R)
      ABV=ABS(V)
      ABQ=ABS(Q)
      ABW=ABS(W)
      ABP=ABS(P)
*KINEMATIC RELATIONS
      RODOT=P+YADOT*SIN(PITCH)
      PIDOT=Q*COS(ROLL)-R*SIN(ROLL)
      YADOT=(R+PIDOT*SIN(ROLL))/COS(PITCH)*COS(ROLL)
      YAWRD=YADOT*57.273
      ROLL=INTGRL(0.,RODOT)
      PITCH=INTGRL(0.,PIDOT)
      YAW=INTGRL(0.,YADOT)
      YAWD=YAW*57.273
      XHDOT=U*COS(YAW) - V*SIN(YAW)
      YHDOT=U*SIN(YAW)+V*COS(YAW)
      XVDOT=U*COS(PITCH)+W*SIN(PITCH)
      ZVDOT=-U*SIN(PITCH)+W*COS(PITCH)
      XH=INTGRL(0.,XHDOT)
      YH=INTGRL(0.,YHDOT)
      XV=INTGRL(0.,XVDOT)
      ZV=INTGRL(000.,ZVDOT)
*SECTION 4 -PROGRAMMED SYMULATION
      I1=-BAA*ADOT-GAA*A-BBA*BDOT-GBA*B-BCA*CDOT-GCA*C...
      -BDA*DDOT-GDA*D-BEA*EDOT-GEA*E-BFA*FDOT-GFA*F+IF1
      I2=-BAB*ADOT-GAB*A-BBB*BDOT-GBB*B-BCB*CDOT-GCB*C...
      -BDB*DDOT-GDB*D-BEB*EDOT-GEB*E-BFB*FDOT-GFB*F+IF2
      I3=-BAC*ADOT-GAC*A-BBC*BDOT-GBC*B-BCC*CDOT-GCC*C...
      -BDC*DDOT-GDC*D-BEC*EDOT-GEC*E-BFC*FDOT-GFC*F+IF3
      I4=-BAD*ADOT-GAD*A-BBD*BDOT-GBD*B-BCD*CDOT-GCD*C...
      -BDD*DDOT-GDD*D-BED*EDOT-GED*E-BFD*FDOT-GFD*F+IF4
      I5=-BAE*ADOT-GAE*A-BBE*BDOT-GBE*B-BCE*CDOT-GCE*C...
      -BDE*DDOT-GDE*D-BEE*EDOT-GEE*E-BFE*FDOT-GFE*F+IF5
      I6=-BAF*ADOT-GAF*A-BBF*BDOT-GBF*B-BCF*CDOT-GCF*C...
      -BDF*DDOT-GDF*D-BEF*EDOT-GEF*E-BFF*FDOT-GFF*F+IF6
*NON LINEAR RELATIONS
      NA=NA1+NA2+NA3+NA4
      NB=NB1+NB2+NB3+NNB
```

```
      NF=NF1+NF2+NF3
      NA1=-LC*(XQQ*Q**2+XRR*R**2+XRP*R*P)
      NA2=-(ML*V*R+XVR*V*R+XWQ*W*Q-ML*W*Q)
      NA3=-(XVV*V**2)/LC
      NA4=-(A1*U**2+A2*U*UC+A3*UC**2)/LC
      NB1=-LC*YPQ*P*Q
      NB2=-(YWP*W*P+YV1R1*V*ABR-ML*U*R+ML*W*P)
      NB3=-(YWV*W*V+Y1V1V*ABV*V)/LC
      NF1=-NPQ*P*Q+(IY-IX)*P*Q
      NF2=-(NWP*W*P+N1V1R*ABV*R)/LC
      NF3=-(NWV*W*V+N1V1V*ABV*V)/LC**2
      IF1=KA1*D1+KA2*D2+KA3*D3+NA
      IF2=KB1*D1+KB2*D2+KB3*D3+NB
      IF3=KC1*D1+KC2*D2+KC3*D3+NC
      IF4=KD1*D1+KD2*D2+KD3*D3+ND
      IF5=KE1*D1+KE2*D2+KE3*D3+NE
      IF6=KF1*D1+KF2*D2+KF3*D3+NF
      ADDOT=(COFAA*I1+COFAB*I2+COFAC*I3+COFAD*I4+COFAE*I5+COFAF*I6)/DEL
      BDDOT=(COFBA*I1+COFBB*I2+COFBC*I3+COFBD*I4+COFBE*I5+COFBF*I6)/DEL
      CDDOT=(COFCA*I1+COFCB*I2+COFCC*I3+COFCD*I4+COFCE*I5+COFCF*I6)/DEL
      DDDOT=(COFDA*I1+COFDB*I2+COFDC*I3+COFDD*I4+COFDE*I5+COFDF*I6)/DEL
      EDDOT=(COFEA*I1+COFEB*I2+COFEC*I3+COFED*I4+COFEE*I5+COFEF*I6)/DEL
      FDDOT=(COFFA*I1+COFFB*I2+COFFC*I3+COFFD*I4+COFFE*I5+COFFF*I6)/DEL
      ADOT=INTGRL(ADOTO,ADDOT)
      BDOT=INTGRL(0.,BDDOT)
      CDOT=INTGRL(0.,CDDOT)
      DDOT=INTGRL(0.,DDDOT)
      EDOT=INTGRL(0.,EDDOT)
      FDOT=INTGRL(0.,FDDOT)
      A=INTGRL(0.,ADOT)
      B=INTGRL(0.,BDOT)
      C=INTGRL(0.,CDOT)
      D=INTGRL(0.,DDOT)
      E=INTGRL(0.,EDOT)
      F=INTGRL(0.,FDOT)
*SECTION 5 -OUTPUT CHARACTERISTICS
 TIMER DELT=0.01,FINTIM=240.0,OUTDEL=1.0,PRDEL=1.0
      PREPARE YH,XH
 END
PARAM DR=-0.4365
END
PARAM DR=-0.6111
END
STOP
```

```
      AAA=XUDCT-ML
      AAB=0.
      AAC=0.
      AAD=0.
      AAE=0.
      AAF=0.
      ABA=0.
      ABB=YVDOT-ML
      ABC=0.
      ABD=0.0
      ABE=0.
      ABF=NVDCT/LC
      ACA=0.
      ACB=0.
      ACC=1.0
      ACD=0.
      ACE=0.
      ACF=0.
      ADA=0.0
      ADB=0.0
      ADC=0.
      ADD=1.0
      ADE=0.
      ADF=0.0
      AEA=0.
      AEB=0.
      AEC=0.
      AED=0.
      AEE=1.0
      AEF=0.
      AFA=0.
      AFB=LC*YRDCT
      AFC=0.
      AFD=0.0
      AFE=0.
      AFF=NRDOT-IZ
*END SECTION 2A
      DEL=VALUE(AAA,0,0)
      CCFAA=VALUE(AAA,1,1)
      CCFAB=VALUE(AAA,2,1)
      CCFAC=VALUE(AAA,3,1)
      CCFAD=VALUE(AAA,4,1)
      CCFAE=VALUE(AAA,5,1)
      CCFAF=VALUE(AAA,6,1)
      CCFBA=VALUE(AAA,1,2)
      CCFBB=VALUE(AAA,2,2)
      CCFBC=VALUE(AAA,3,2)
      CCFBD=VALUE(AAA,4,2)
```

```
        CCFBE=VALUE(AAA,5,2)
        CCFBF=VALUE(AAA,6,2)
        CCFCA=VALUE(AAA,1,3)
        CCFCB=VALUE(AAA,2,3)
        CCFCC=VALUE(AAA,3,3)
        CCFCD=VALUE(AAA,4,3)
        CCFCE=VALUE(AAA,5,3)
        CCFCF=VALUE(AAA,6,3)
        CCFDA=VALUE(AAA,1,4)
        CCFDB=VALUE(AAA,2,4)
        CCFDC=VALUE(AAA,3,4)
        CCFDD=VALUE(AAA,4,4)
        CCFDE=VALUE(AAA,5,4)
        CCFDF=VALUE(AAA,6,4)
        CCFEA=VALUE(AAA,1,5)
        CCFEB=VALUE(AAA,2,5)
        CCFEC=VALUE(AAA,3,5)
        CCFED=VALUE(AAA,4,5)
        CCFEE=VALUE(AAA,5,5)
        CCFEF=VALUE(AAA,6,5)
        CCFFA=VALUE(AAA,1,6)
        CCFFB=VALUE(AAA,2,6)
        CCFFC=VALUE(AAA,3,6)
        CCFFD=VALUE(AAA,4,6)
        CCFFE=VALUE(AAA,5,6)
        CCFFF=VALUE(AAA,6,6)
DYNAMIC
        DCC=-DR*57.273
        X=TIME
        KA1=-XDRDR*U*U*DR/LC
        KB1=-YDR*U*U/LC
        KC1=-KDR*U*U/LC**2
        KF1=-NDR*U*U/LC**2
        BBB=U*YV/LC
        BBC=U*KV/LC**2
        BBF=U*NV/LC**2
        BCB=U*YP
        BCC=U*KPC/LC
        BCF=U*NP/LC
        BFB=U*YR
        BFC=U*KR/LC
        BFF=U*NR/LC
*SECTION 3-DEFINITIONS
        UDOT=ADDOT
        U=ADOT
        VDOT=BDDOT
        V=BDOT
        WDOT=CDDOT
```

```
      FUNCTION VALUE(Y,I,M)
COMMON
      DIMENSION X(6,6),Y(6,6)
      DO 1 M1=1,6
      DO 1 M2=1,6
    1  X(M1,M2)=Y(M1,M2)
      IF(I.EQ.0) GO TO 100
      X(I,1)=0.
      X(I,2)=0.
      X(I,3)=0.
      X(I,4)=0.
      X(I,5)=0.
      X(I,6)=0.
      X(1,M)=0.
      X(2,M)=0.
      X(3,M)=0.
      X(4,M)=0.
      X(5,M)=0.
      X(6,M)=0.
      X(I,M)=1.
  100 CONTINUE
      WRITE(6,49) I,M
   49 FORMAT(/,' ','DETERMINANT FOR COF',I1,I1,':')
      DO 50 M1=1,6
      WRITE(6,51)(X(M1,M2),M2=1,6)
   51 FORMAT(10(1X,E13.6))
   50 CONTINUE
      N=6
      DD=1.D0
   10  DO 34 L=1,N
       KP=0
       Z=0.0
       DO 12 K=L,N
      IF(Z-ABS(X(K,L)))11,12,12
   11 Z=ABS(X(K,L))
       KP=K
   12  CONTINUE
       IF(L-KP)13,20,20
   13  DO 14 J=L,N
       Z=X(L,J)
       X(L,J)=X(KP,J)
   14  X(KP,J)=Z
      DD=-DD
   20  IF(L-N)31,40,40
   31  LP1=L+1
       DO 34 K=LP1,N
       IF(X(K,L))32,34,32
   32  RATIO=X(K,L)/X(L,L)
```

```
      DO 33 J=LP1,N
33    X(K,J)=X(K,J)-RATIO*X(L,J)
34    CONTINUE
40    DO 41 K=1,N
41    DD=DD*X(K,K)
      D=DD
      VALUE=D
      WRITE(6,52) I,M,VALUE
52    FORMAT(' ','COF',I1,I1,'=',E15.6)
      RETURN
      END
ENDJOB
```

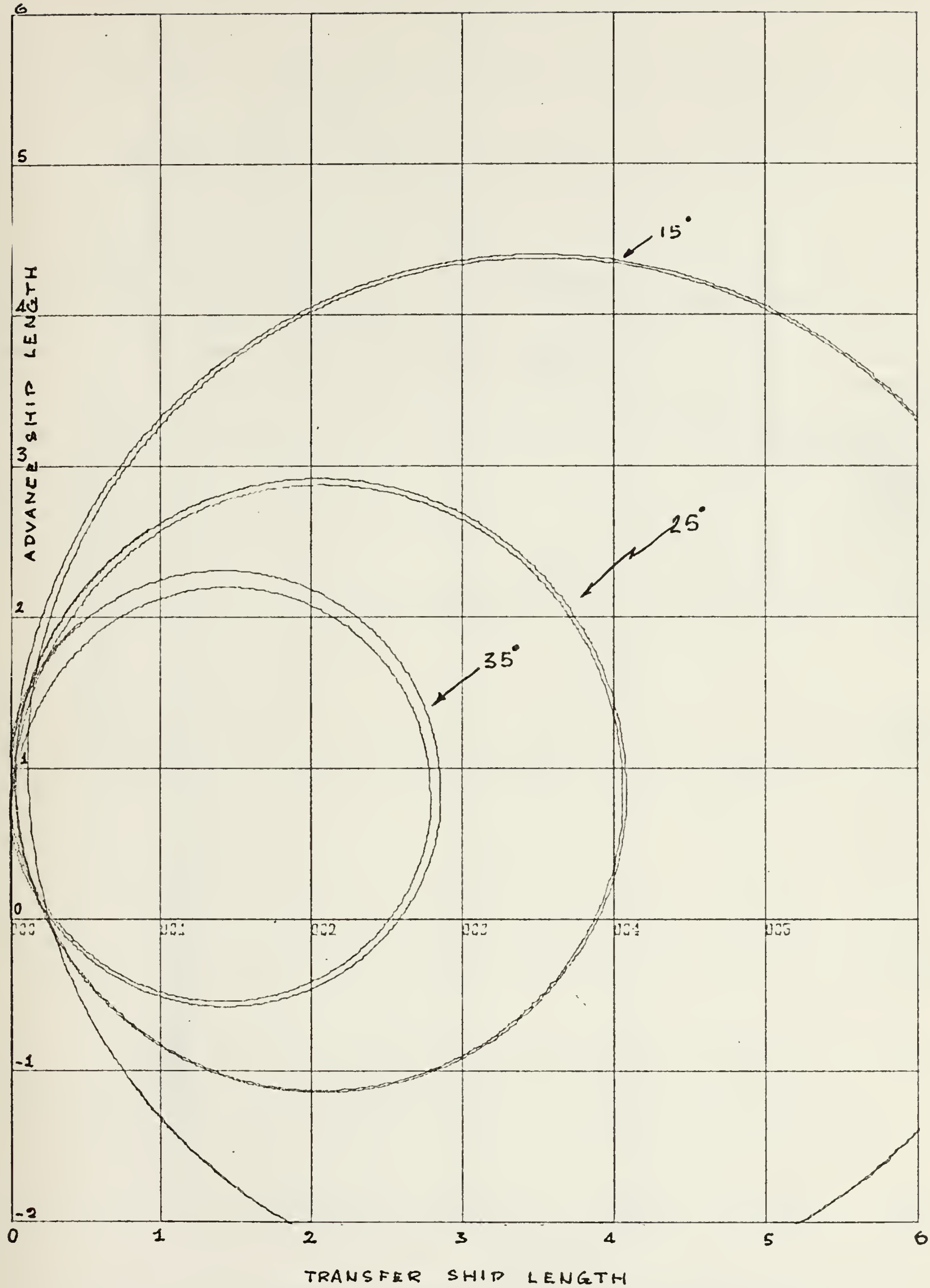

FIG. 8 ADVANCE VS. TRANSFER SHIP LENGTH (DR = 15°, 25° & 35°)

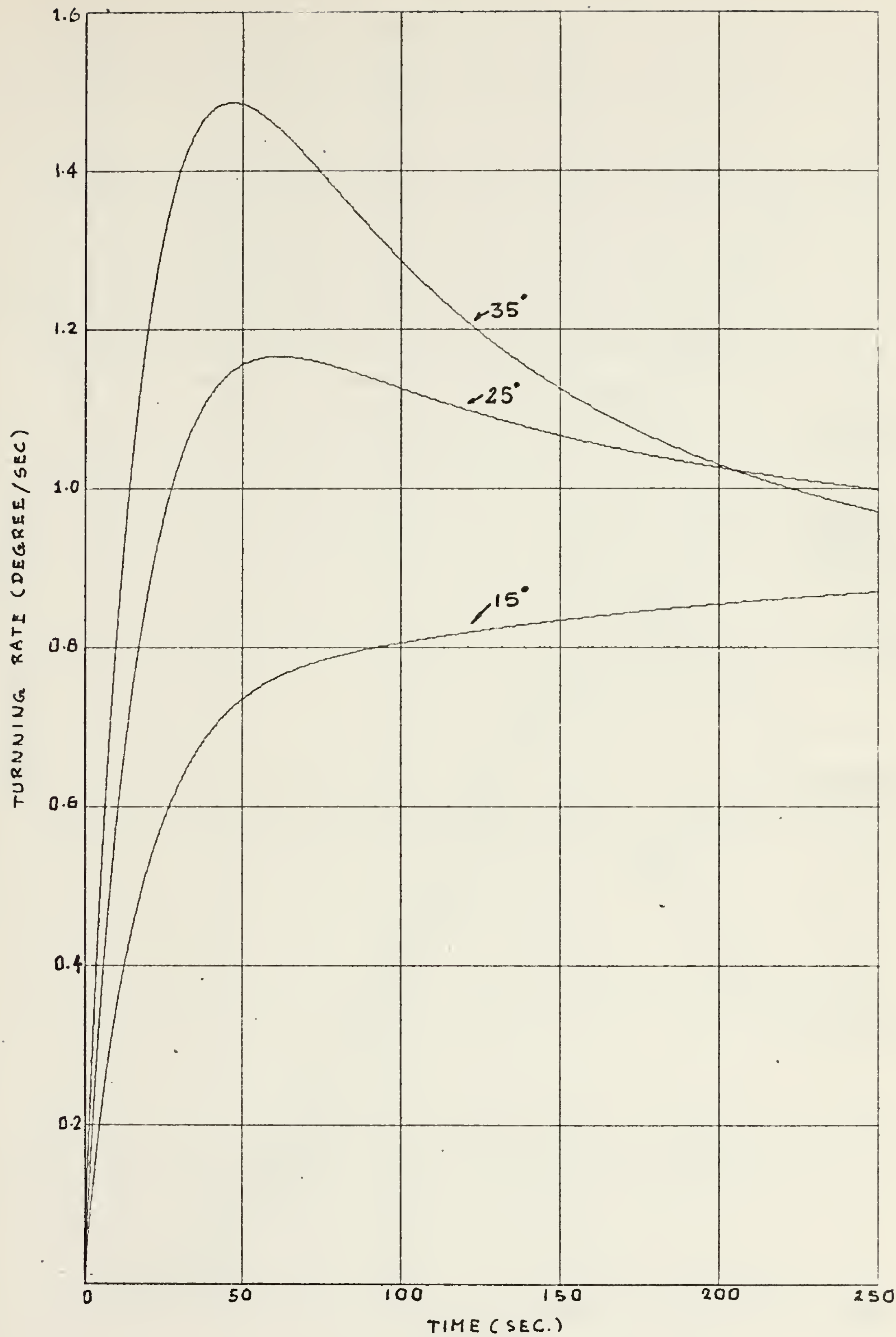

FIG. 9 TURNING RATE AS A FUNCTION OF TIME
(RUDDER 15°, 25 & 35°)

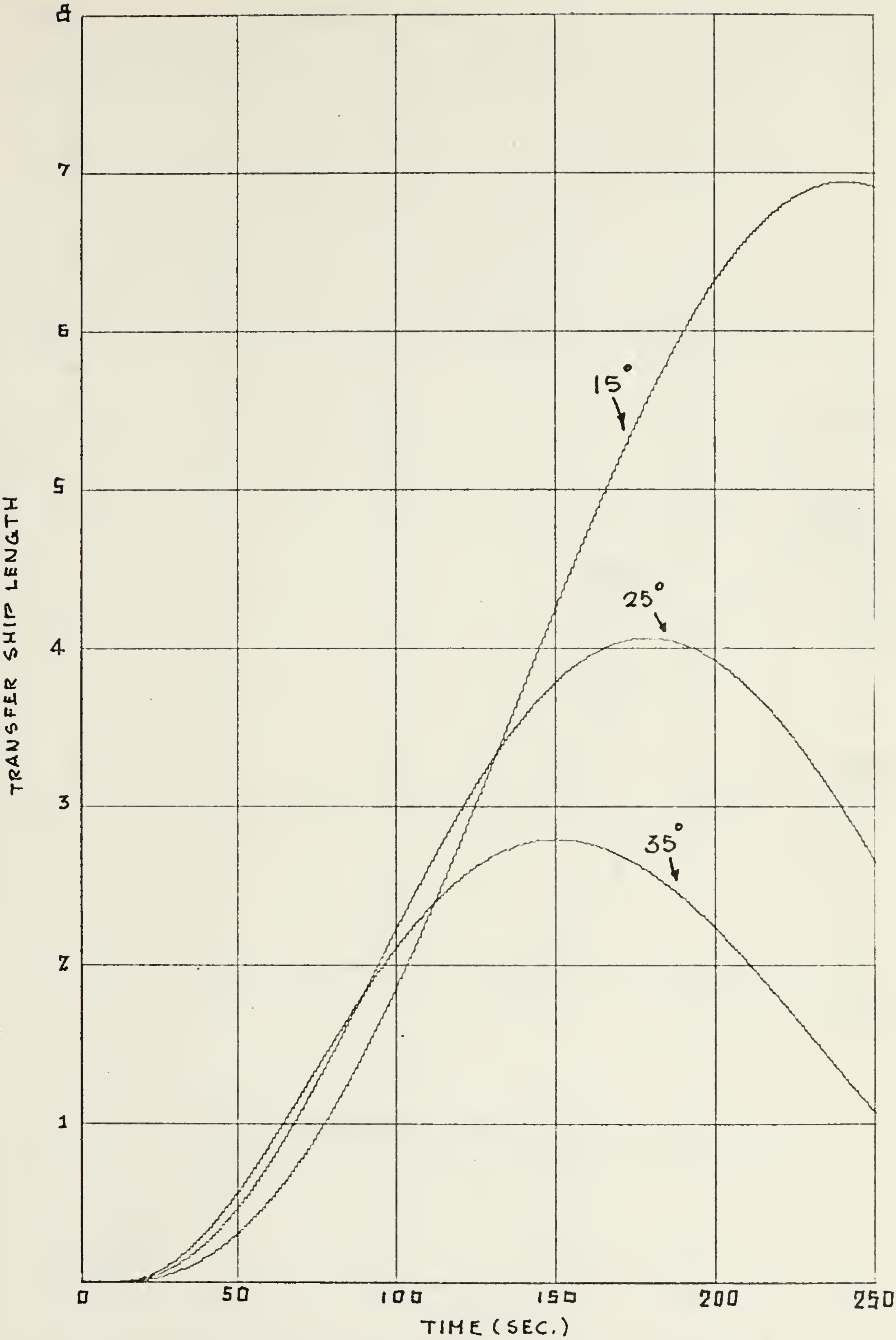

FIG. 10 TRANSFER SHIP LENGTH VS. TIME
(RUDDER 15°, 25° & 35°)

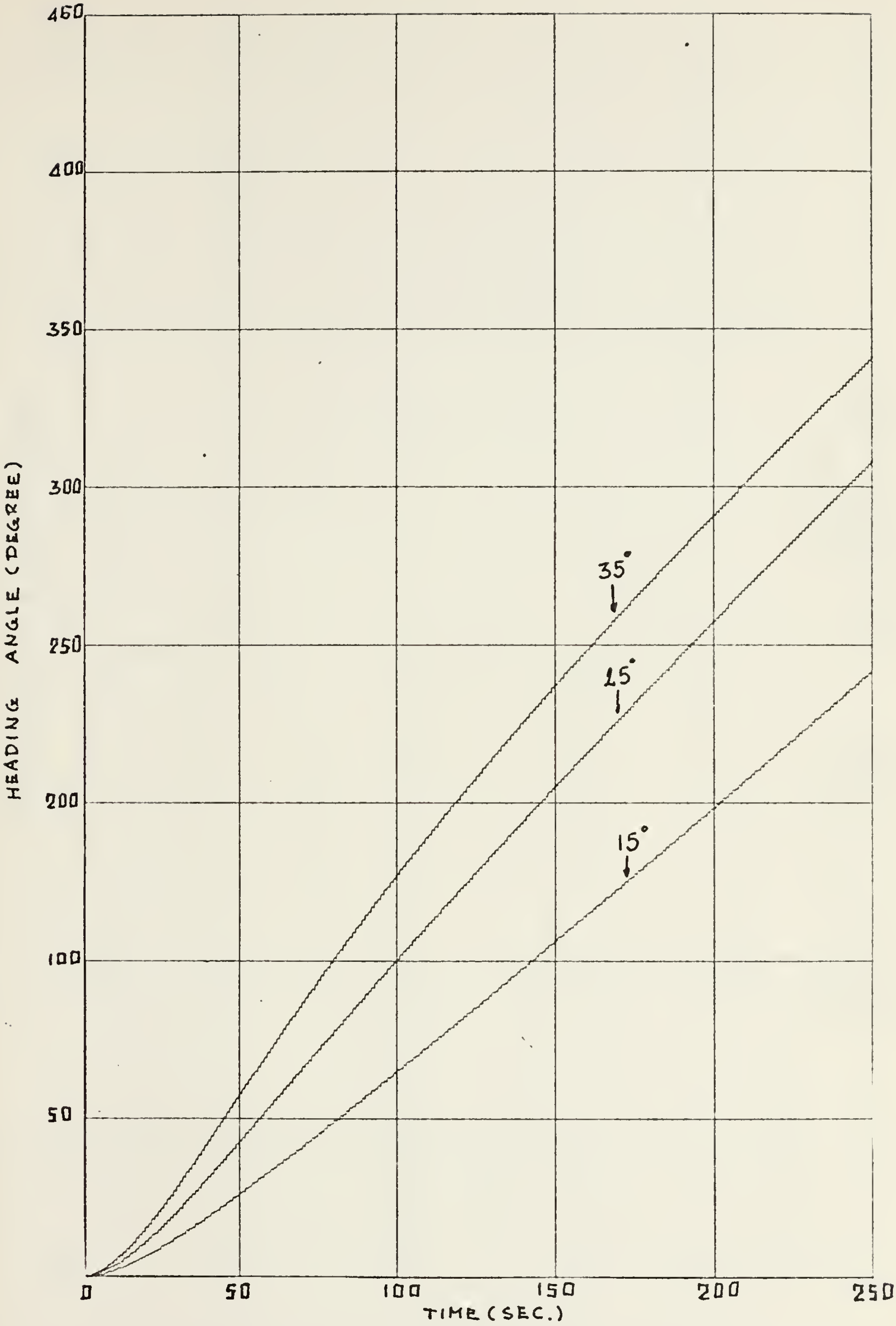

FIG. 11 HEADING ANGLE AS A FUNCTION OF TIME

(RUDDER 15°, 25° & 35°)

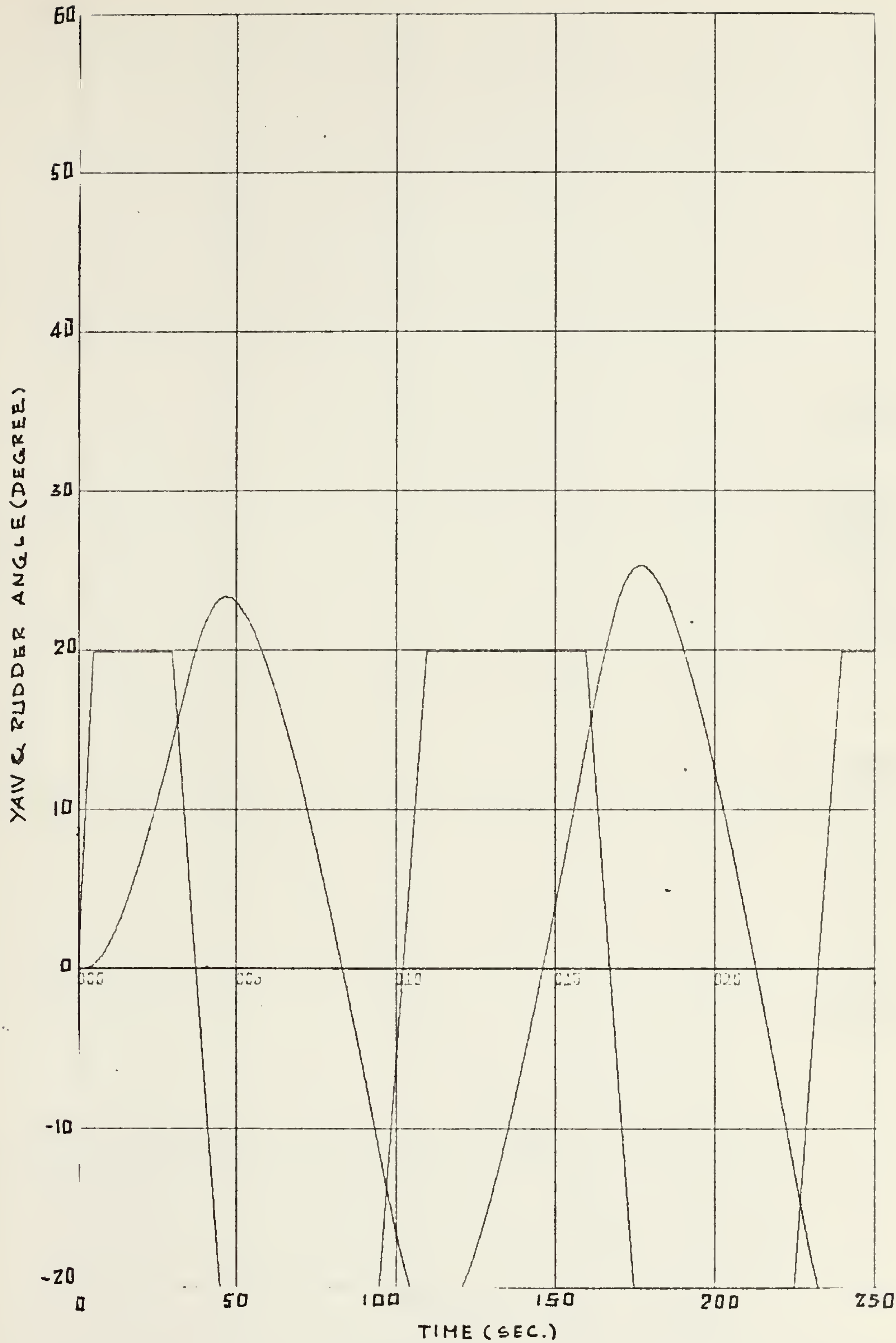

FIG. 12 YAW & RUDDER ANGLE VS. TIME (ZIG-ZAG MANOEUVER)

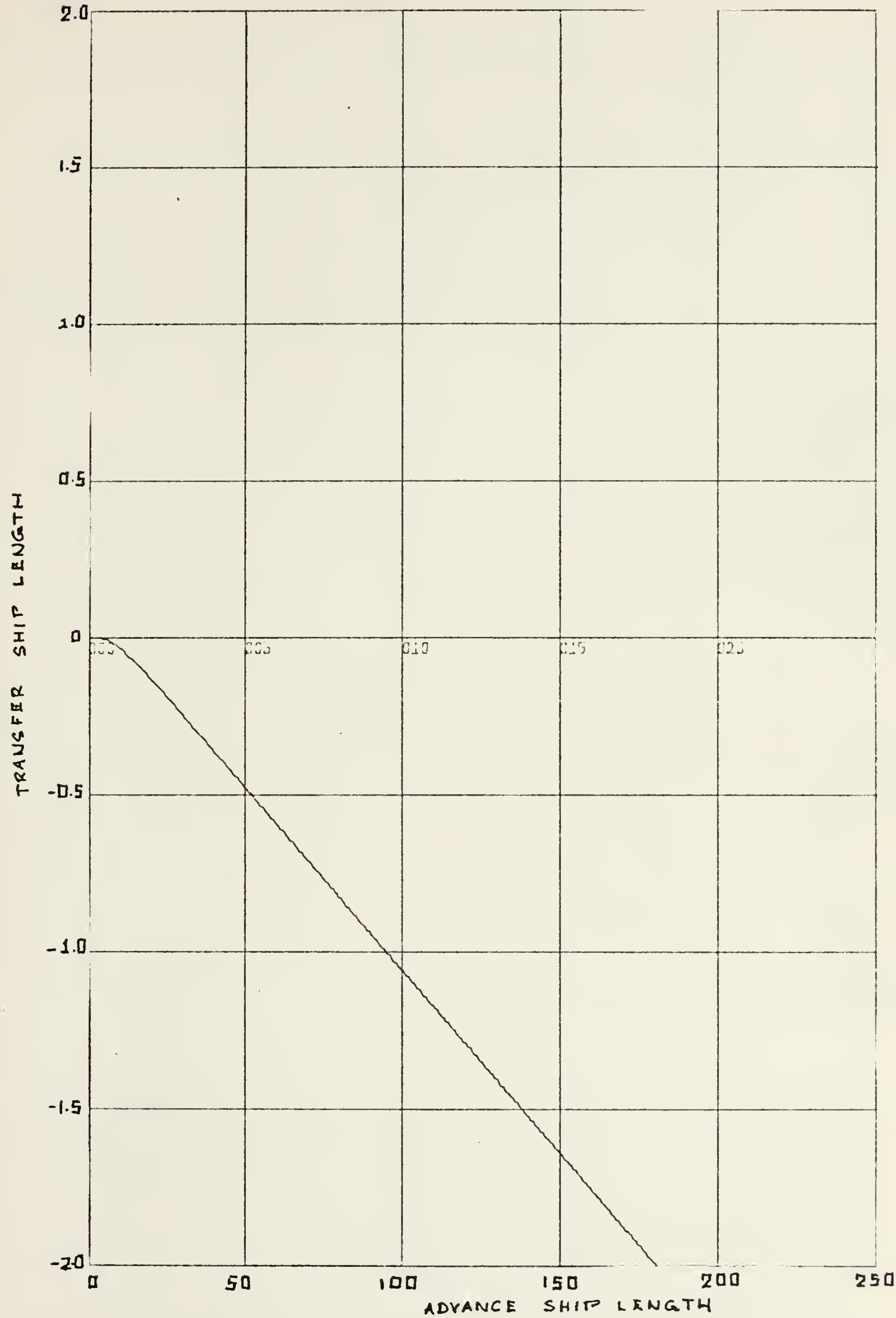

FIG. 13 DIRECTION OF THE SHIP WHEN EXTERNAL MOMENT FORCE APPLIED TO THE SHIP

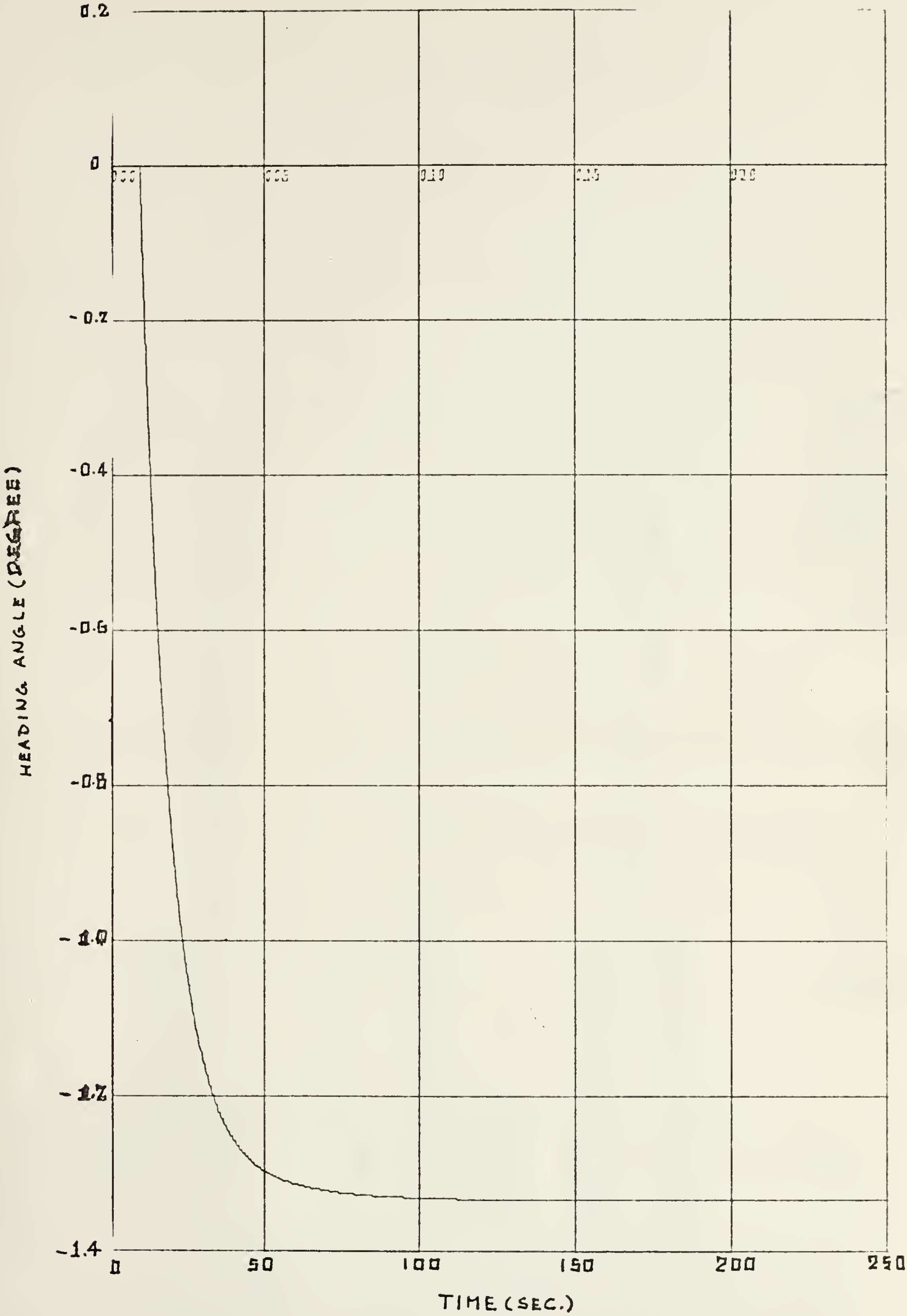

FIG. 14 HEADING ANGLE VS. TIME
(APPLIED FORCING MOMENT TO THE SHIP)

COMPUTER PROGRAM 3

```
      DIMENSION XOUT(50),X(900),Y(900),Z(900),TYPE(2)
      REAL*8  LABEL/8H        /,ITITLE(12),BLANK/'        '/,TGRL,VAR1,
     1VAR2,VAR3,VAR4,VAR5,VAR6,TEST
      DATA ENDS/'ENDS'/
      DOUBLE PRECISION WORD
      KGRAPH=3
      READ(5,7) NOPLOT
   16 READ(5,7) NOCUR
    7 FORMAT(I3)
      READ(5,1) (ITITLE(I),I=1,6)
      READ(5,1) (ITITLE(I),I=7,12)
    1 FORMAT(6A8)
      READ(5,2)  XSCALE,YSCALE,IUP,IRITE,MODEX,MODEY,IW,IHI,IGR
    2 FORMAT(2F5.0,7I5)
      IF(NOCUR-1)  14,10,11
   10 MODCUR=0
      GO TO 15
   11 MODCUR=1
   15 CONTINUE
      DO 3 I=1,10
    3 READ  (15) WORD
      READ (15) WORD
      NUMPTS=0
    6 READ (15) (XOUT(I),I=1,KGRAPH)
      IF (XOUT(1) - ENDS) 8,9,8
    8 NUMPTS = NUMPTS + 1
      Z(NUMPTS)=XOUT(1)
      X(NUMPTS)=XOUT(2)
      Y(NUMPTS)=XOUT(3)
      GO TO 6
    9 CONTINUE
      DO 18 I=1,NUMPTS
      WRITE (6,19) X(I),Y(I),Z(I)
   19 FORMAT (5X,F20.4,10X,F20.4,10X,F20.4)
   18 CONTINUE
      CALL DRAW(NUMPTS,X,Y,MODCUR,0,LABEL,ITITLE,XSCALE,YSCALE,IUP,IRITE
     1,MODEX,MODEY,IW,IHI,IGR,LAST)
      NOCUR = NOCUR - 1
      IF(NOCUR - 1) 14,12,13
   12 MODCUR = 3
      READ (15) WORD
      GO TO 15
   13 MODCUR = 2
      READ (15) WORD
      GO TO 15
   14 NOPLOT = NOPLOT - 1
      READ(15) WORD
```

```
      IF(NCPLCT)  17,17,16
   17 STOP
      END
```

IV. CONCLUSIONS

The equation of motion of surface ship and computer program developed here including all of six degrees of freedom, but the study in III concerns only three degrees of freedom (surge, sway, yaw) because hydrodynamic coefficients are not available; when the state of the art reaches the stage in which hydrodynamics coefficients are available, this computer program can be used in all six degrees of freedom.

Some results from III are not too perfect because the lack of some constants and coefficients such as the value of mass (m), initial velocity (ADOTO), command speed (UC), etc. But for study can adjust from curve for the model test [Ref. 6].

This computer program did not include some external effects such as effects of wave and wind, but these effects could be included in the program by adding terms to the IF equation.

The following implementations are suggested for the future work.

A. Study all six degrees of freedom.

B. Study for the effects of waves and wind.

C. Study for control of the velocity and direction of the ship (by use of "MACROS', "PROCEDURE" or subprogram in CSMP).

LIST OF REFERENCES

1. Abkowitz, Martin A.: Stability and Motion Control of Ocean Vehicles. The MIT Press, 1969.

2. George J. Thaler: Ship Control System. Naval Postgraduate School, 1973.

3. System/360 Continuous System Modeling Program, the IBM Press GH20-0367-4.

4. Edgar Romero: Mathematical Models and Computer Solution for the Equations of Motion of Surface Ships and Submarines, in Six Degrees of Freedom. Thesis, Naval Postgraduate School, 1972.

5. Technical and Research Bulletin No. 1-5, Society of Naval Architect and Marine Engineers.

6. Report for ship "D" of NSRDC (Naval Ship Research and Development Center).

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Professor M. L. Wilcox, Code 52Wx Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	2
4.	Dr. G. J. Thaler, Code 52Tr Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
5.	Professor A. Gerba, Jr., Code 52Gz Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
6.	Lieutenant Commander Aporn Ratanaruang Royal Thai Navy Bangkok, Thailand	3
7.	Professor D. M. Layton, Code 57Ln Aeronautical Engineering Department Naval Postgraduate School Monterey, California 93940	1
8.	Library, Planning & Design Division Thai Naval Shipyard Bangkok, Thailand	1
9.	Education Section Personal Department Royal Thai Navy Bangkok, Thailand	1

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

ORIGINATING ACTIVITY (Corporate author) aval Postgraduate School onterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

REPORT TITLE

Digital Computer Simulation for Surface Ship Control

DESCRIPTIVE NOTES (Type of report and, inclusive dates)

Master's Thesis; June 1973

AUTHOR(S) (First name, middle initial, last name)

Aporn Ratanaruang

REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1973	67	6

CONTRACT OR GRANT NO. PROJECT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Postgraduate School Monterey, California 93940

ABSTRACT

The general equations of surface ship motion are developed and standardized for simulation in digital computer. Digital simulations of the dynamics of the surface ship in three degrees of freedom are done with and without non-linear and cross-coupling terms.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
ship control						
surface ship in six degrees of freedom						
ship maneuvering						
simulation						

Thesis
R24
c.1

145211

Ratanaruang

Digital computer simulation for surface ship control.